REVIEW OF:

DOE STUDY PLAN 8.3.1.8.5.1
Characterization of Volcanic Features (Revision 1), Dated March 1993

Prepared for

Nuclear Regulatory Commission
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by

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1 REGULATORY BASIS FOR REVIEW

Staff at the U.S. Nuclear Regulatory Commission (NRC) is required to review and evaluate the license application of the U.S. Department of Energy (DOE) for the proposed High-Level Waste (HLW) geologic repository at Yucca Mountain, Nevada. Requirements of post-closure performance are set forth by the Environmental Protection Agency (EPA) in 40 CFR Part 191 and by the NRC in 10 CFR Part 60. Because of the possible impact of volcanism on repository performance, two conditions specifically related to volcanism are included in siting criteria in 10 CFR 60.122(c)(3), potential changes in groundwater flow as a result of igneous activity, and 10 CFR 60.122(c)(15), evidence of igneous activity in the Quaternary Period (i.e., within the last 1.6 m.y.).

DOE Study Plan 8.3.8.5.1, *Characterization of volcanic features*, is written to describe research intended to resolve issues related to volcanism as part of site characterization. These goals include development of data sets that will be used to assess the probability of volcanic eruptions in the region and at the HLW repository site in particular during the next 10,000 yr., and to assess the consequences of this potential volcanic activity on repository performance. Field investigations described in Study Plan 8.3.1.8.5.1 include: volcanism drill holes (activity 8.3.1.8.5.1.1), geochronological studies (activity 8.3.1.8.5.1.2), field geologic studies (activity 8.3.1.8.5.1.3), geochemistry of eruptive sequences (activity 8.3.1.8.5.1.4), and evolutionary cycles of basaltic volcanic fields (activity 8.3.1.8.5.1.5).

The NRC intends to provide guidance to the DOE during prelicensing activities so that technical issues related to site characterization and performance assessment (PA), can be resolved in a timely and rigorous manner. The NRC Office of Nuclear Material Safety and Safeguards (NMSS) has requested that the Center for Nuclear Waste Regulatory Analyses (CNWRA) provide a technical review of DOE Study Plan 8.3.1.8.5.1. This review concentrates on the review of technical aspects of the volcanism site characterization research program, rather than quality assurance or programmatic issues. Aspects of the technical review include:

- Assessment of the technical methods used in the characterization of volcanic features
- Analysis of the utility of the proposed research program to the resolution of technical issues related to probability and consequences of potential volcanism in and near the candidate repository site
- Identification of research areas that may provide critical information in site characterization that are not described in Study Plan 8.3.1.8.5.1

These aspects of the technical review are directly related to activities described in the License Application Review Plan (LARP). The LARP indicates that it is necessary to investigate the possible magnitude of volcanic eruptions likely to occur in the Yucca Mountain Region (YMR) in the event of future volcanic activity, the areas likely affected, the likely duration of volcanic activity (evidence of igneous activity as a potentially adverse condition, LARP section 3.2.1.9, and impact of volcanism on groundwater movement, LARP section 3.2.2.7), and to describe overall system performance (assessment of compliance with the requirement for cumulative releases of radioactive materials, LARP section 6.1). Compliance Determination Strategies (CDS) for these LARP sections are currently under development. The CDS associated with evidence of Quaternary volcanism indicate (i) that independent research must be conducted to evaluate Key Technical Uncertainties (KTU) associated with volcanism and (ii) that volcanism poses a high risk of noncompliance with 40 CFR Part 191 as set forth by the Environmental Protection Agency and 10 CFR 60.122(c)(15) as determined by the NRC. To date, three KTU related to igneous activity have been identified as a result of concern with evidence of Quaternary igneous activity. These KTU are:

- Low resolution of exploration techniques to detect and evaluate igneous features
- Inability to sample igneous features
- Development and use of conceptual tectonic models as related to igneous activity

Evaluation of these KTU will require detailed safety reviews supported by independent tests, analyses, and related investigations. Each of these KTU has been established independent of DOE activities and will be investigated as research programs at the CNWRA. Nonetheless, it is important to evaluate the effectiveness of DOE research with respect to these KTU, as they must be resolved by scientific investigation in the prelicensing stage.

Formal comments are presented following the organization of the DOE Study Plan itself, with comments divided into sections that are used in the Study Plan. In some cases, comments are directed toward research not addressed specifically in the Study Plan, for instance those areas in which alternative investigations are called for. These areas of research are provided within the section that seems most appropriate. Each comment consists of:

- *Statement of Concern.* The statement of concern provides a question or comment on a specific section, or comments on the need for alternative or additional research on a specific technical issue.
- *Basis.* The technical basis for the statement of concern is described, and usually involves discussion of alternative data, models, or research that may need to be addressed.
- *Recommendation.* The recommendation is intended to offer alternative approaches or appropriate revisions that will help better address volcanism issues related to site characterization.
- *References.* A list of references cited within the comment.

Following these detailed comments, the major points raised in this review are summarized.

2 SPECIFIC TECHNICAL COMMENTS

2.1 VOLCANISM DRILL HOLES

Comment 2.1.1

Statement of Concern: Section 2.1.1 details plans to delineate buried volcanic features in the YMR through use of drill-hole data, based on currently available high-quality aeromagnetic data. These aeromagnetic data cannot resolve magnetic anomalies associated with all intrusions in adequate detail. What other geophysical or volcanological studies are planned to assess the volume of extrusive-to-volume of intrusive ratio in the YMR? Characterization of this ratio is important and is not discussed in the Study Plan.

Basis: Probability models developed to date have dealt almost exclusively with the probability of a volcanic event in the YMR during the containment period (10,000 years). These models, with the notable exception of Sheridan (1992), do not deal with the likelihood of intrusion to repository depths without accompanying volcanic activity. This omission is largely because the extrusive-to-intrusive ratio is not known for the area. Crowe et al. (1993) have suggested that this ratio is one-to-one, that is, no intrusions occur in the YMR that reach depths of 300 m or less, without accompanying eruptions. This 1:1 ratio is based on the lack of aeromagnetic anomalies and the idea that if magmas reach a shallow depth, then these magmas are likely to reach the surface (Crowe et al., 1993).

Aeromagnetic data of the type collected in the region (Kane and Bracken, 1983) are not capable of resolving anomalies associated with thin (< 5 m in width), shallow dikes in alluvial basins, even at depths of less than 100 m. Characteristic curves can be used to illustrate this point. Furthermore, total magnetization contrast is small between dikes and the welded tuffs of the repository block and related areas. This small contrast further reduces the possibility of detecting thin shallow dikes.

Work in other areas indicates that extrusive-to-intrusive ratios are normally quite low. At mid-ocean ridges, this ratio is often 0.1 to 0.3 based on investigations of ophiolite sections (e.g., Nicolas, 1989) and 0.1 to 0.25 based on seismic investigations of mid-ocean ridges (e.g., Harding et al., 1989). These values are similar to those proposed for Kilauea (Shaw, 1987) and Krafla (Björnsson, 1985). In continental settings, the ratio might be quite different because of different rock densities, rock mechanical strengths, and the presence of pre-existing structures. Kurtz et al. (1986) identified very shallow dike intrusions in the Craters of the Moon field that did not result in extrusive activity. The 1980 activity at Long Valley caldera may provide another example of a dike reaching shallow depths in a continental setting without erupting. This example seems relevant because, although magma did not reach the surface, changes in hydrothermal activity and soil degassing were noted to result from this intrusion (e.g., Mastin and Pollard, 1988; Sorey et al., 1993). These occurrences indicate that shallow degassing from dikes does occur on continents in some geologic settings. To our knowledge, there is not a single example of a volcanic field in which the extrusive-to-intrusive ratio is known to be as high as one-to-one, nor is an example cited in the Study Plan.

Recommendation: Further effort should be invested in characterizing the ratio of extrusive events to intrusive events that reach to within, for example, 1 km of the surface. This effort should involve investigation in analog areas, such as Paiute Ridge (as undertaken by Valentine et al., 1992), and similar areas. This type of investigation will have direct impact on probability models. Such investigations might include geological mapping and ground geophysical studies, complementing review of the literature.

References:

Björnsson, A. 1985. Dynamics of crustal rifting in NE Iceland. *Journal of Geophysical Research* 90: 10,151-10,162.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Harding, A.J., J.A. Orcutt, M.E. Kappus, E.E. Vera, J.C. Mutter, P. Buhl, R.S. Detrick, and T.M. Brocher. 1989. Structure of the young oceanic crust at 13 °N on the East Pacific Rise from expanding spreading profiles. *Journal of Geophysical Research* 94: 12,163-12,196.

Kane, M.F., and R.E. Bracken. 1983. Aeromagnetic map of Yucca Mountain and surrounding regions, southwest Nevada. *U.S. Geological Survey Open-File Report* 83-616.

Kurtz, M.A., D.E. Champion, E.C. Spiker, and R.H. Lefebvre. 1986. Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho. *Geological Society of America, Bulletin* 97: 579-594.

Mastin, L.G., and D.D. Pollard. 1988. Surface Deformation and Shallow Dike Intrusion Process at Inyo Craters, Long Valley, California. J. Geophysical Research 90: 11,121-11,126.

Nicolas, A. 1989. *Structures of Ophiolites and Dynamics of the Oceanic Lithosphere*. Kluwer Academic Publishers: Dordrecht, 493 pp.

Shaw, H.R. 1987. Uniqueness of volcanic systems. *Volcanism In Hawaii.* R.W. Decker, T.L. Wright, and P. Stauffer, eds., Reston, VA: U.S. Geological Survey. U.S. Geological Survey Professional Paper 1350: 1,357-1,394.

Sheridan, M.F. 1992. A Monte-Carlo technique to estimate the probability of volcanic dikes. *Proceedings of the Third International Conference on High-Level Radioactive Waste Management:* La Grange Park, IL: American Nuclear Society: 2: 2,033-2,038.

Sorey, M.L. B.M. Kennedy, W.C. Evans, C.D. Farrar, and G.A. Suemnicht. 1993. Helium-Isotope and Gas-Discharge Variations Associated with Crustal Unrest in Long Valley Caldena, California. 1989-1992. J.G.R.: In Press.

Valentine, G.A., B.M. Crowe, and F.V. Perry. 1992. Physical processes and effects of magmatism in the Yucca Mountain region. *Proceedings of the Third International Conference of High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society 2: 2,014-2,024.

Comment 2.1.2

Statement of Concern: It is mentioned in section 2.1.1 that magnetic polarities will be determined using a fluxgate magnetometer. This method is not appropriate for determining all rock magnetic properties that may be important.

Basis: A fluxgate magnetometer alone cannot distinguish virtual remnant magnetization (VRM) from other, more relevant magnetic components. This determination can only be done after alternating frequency demagnetization. This cleaning is sometimes needed because a VRM overprint can give spurious results. Determination of susceptibility and thermoremnant magnetization is important to models based on interpretation of aeromagnetic and ground magnetic data, and these properties are best determined using standard rock magnetic techniques.

Recommendation: It is suggested that samples be analyzed in a rock magnetics laboratory and that the VRM component be removed prior to estimation of polarity.

Comment 2.1.3

Statement of Concern: Section 5 of Crowe et al. (1993) mentions that it may be important to characterize intrusion geometries associated with the development of the Little Cones-Northern Cone alignment. No mention is made in the Study Plan of methods for better characterizing these intrusive geometries. Reaching a better understanding of the development of this cinder cone alignment would have direct bearing on probability and consequence studies. Therefore, further field investigation into the nature of this alignment seems warranted.

Basis: In section 5 of Crowe et al. (1993), it is indicated that the Crater Flat cinder cone alignment might be related to a single set of dikes. For example, bladed dikes might extend outward from the Red Cone - Black Cone pair in NE and SW directions, feeding other, smaller cinder cones (Crowe et al., 1993). Although this idea may not be consistent with geochronological and geochemical data, it has important implications for probability models. For example, the Crater Flat alignment might be considered to be a single, long-lived volcanic feature, rather than a series of discrete events. Geophysical methods, such as ground magnetic or electrical surveys might be used to test the hypothesis that bladed dikes occur along the entire length of the cinder cone alignment. Ground magnetic data can be collected rapidly and inexpensively along traverses with short sample spacing (e.g., 5 m) in the alluvium between these volcanoes. Electrical methods that might be employed include the mise-a-la-masse method (e.g., Beasley and Ward, 1986), which is used extensively in the mining industry to track the lateral extent of ore veins. In this context, current could be induced in dikes that outcrop, SW of Little Cone for example, and the resulting potential field mapped at the surface. The resolution of this method would need to be assessed based on differences in conductivity between the dike and alluvium. Aeromagnetic surveys probably would not be successful at delineating the proposed dikes, due to topographic effects associated with magnetized basaltic cones and the small amplitude of the magnetic anomaly that would be associated with the proposed dikes.

Recommendation: Consider field geophysical methods that can be used to identify shallow dike orientations and lengths along the Crater Flat volcano alignment. Some success might be gained using ground magnetic and electrical methods near Little Cones and Northern Cone to get an idea of the lateral extent and orientation of dikes associated with these cones. Such surveys, for example, might help delineate the relationship between the Little Cones and the dike reported to the southwest of these cones

(Crowe et al., 1993). This relationship would have direct impact on probability models by influencing recurrence rate estimates and estimates of the areal extent over which single events occur. If anomalies can be identified, directional drilling should be considered as a methods of sampling the anomalies.

References:

Beasley, C.W., and S.H. Ward. 1986. Three-dimensional mise-a-la-masse modeling applied to mapping fracture zones. *Geophysics* 51: 98-113.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Comment 2.1.4

Statement of Concern: Seismic tomographic methods may provide direct insight into magmatism in the YMR and should be considered in the context of this report. Because tomographic surveys may provide independent tests of the waning magmatism hypothesis, the utility of such data should be discussed as part of a site characterization of volcanic features. How will tomographic data be integrated into volcanological site characterization as the project continues?

Basis: Although the use of seismic data is discussed in Study Plan 8.3.1.8.1, it is important to realize that seismic tomographic data may provide direct information about the presence of magma bodies. This presence should be considered a part of basic site characterization of volcanic features. Furthermore, seismic tomographic surveys may need to be tailored specifically to address volcanological problems.

As may be the case with ground magnetic surveys, seismic tomographic surveys are a geophysical method that could provide extensive information on volcanism issues related to the persistence of magmatism in the region, and the likelihood of future magmatic activity. Numerous studies have demonstrated the utility of detailed active and passive seismic tomographic surveys in volcanic areas (e.g., Sanders et al., 1989; Achauer et al., 1986; Iyer, 1984; Nercessian et al., 1984), and lower resolution surveys have indicated the presence of low-velocity zones in the YMR (Evans and Smith, 1992). Given the broad use of seismic tomographic methods in delineating structure and low-velocity zones in volcanic areas, and the presence of a low-velocity anomaly in the YMR, it is important to integrate these methods into the volcanism site characterization process.

Recommendation: Some plan should be formulated to specifically address how seismic tomographic data and other geophysical investigations will be incorporated into site characterization of volcanic features. This incorporation will be necessary because it is likely that probability models will depend on interpretation of these data.

References:

Achauer, U., L. Greene, J.R. Evans, and H.M. Iyer. 1986. Nature of the magma chamber underlying the Mono Craters area, eastern California, as determined from teleseismic traveltime residuals. *Journal of Geophysical Research* 91: 13,873-13,891.

Evans, J.R., and M. Smith III. 1992. Teleseismic tomography of the Yucca Mountain Region: volcanism and tectonism. *Proceedings of the Third International Conference of High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 2: 2,371-2,380.

Iyer, H.M. 1984. Geophysical evidence for the location, shapes and sizes, and internal structures of magma chambers beneath regions of Quaternary volcanism. *Philosophical Transactions of the Royal Society, London* A 310: 473-510.

Nercessian, Al., Al. Hirn, and Al. Tarantola. 1984. Three-dimensional seismic transmission prospecting of the Monte Dore volcano, France. *Geophysical Journal of the Royal Astronomical Society* 76: 307-315.

Sanders, C.O., P. Ho-Liu, and D. Rinn. 1989. Anomalous shear wave attenuation in the shallow crust beneath the Coso volcanic region, California. *Journal of Geophysical Research* 93: 3,321-3,338.

2.2 Geochronology

Comment 2.2.1

Statement of Concern: As discussed in the Study Plan, the ages of the Quaternary Crater Flat volcanoes are insufficiently precise to permit the development of robust volcanological models. It is not clear in the Study Plan if additional dates will be determined for Quaternary or Neogene volcanic rocks of the YMR, or if the currently available dates, which have large uncertainties, will be used in subsequent models.

Basis: Based on the data presented in Crowe et al. (1993), a reasonable estimate of the age of the Quaternary Crater Flat volcanoes is 1.2±0.4 Ma.

- Northern Cone: There are only two published dates for this center, which average 1.1±0.3 Ma.

- Black Cone: Two dates of 1.09±0.3 and 1.07±0.4 Ma are reported.

- Red Cone: A total of 23 dates have been reported for Red Cone. A wide range of dates from 0.95±0.08 to 1.9±0.2 Ma is reported with an averate date of 1.4.±0.6 Ma.

- Little Cones: The only apparent date of 1.11±0.3 Ma is from a reported feeder dike exposed in a small scoria cone 0.5 km SE of the southern Little Cone. There are apparently no dates for the main cone of the southern Little Cone or for the amphibole-bearing northern Little Cone.

The Quaternary Crater Flat volcanoes may have erupted at resolvably different times. The development of distinct soil profiles between Red and Black Cones (Wells et al., 1990) likely indicates that an age difference exists between these centers. Soil profiles apparently are similar for the Little Cones and Black Cone, which may indicate a similar age for these vents. Soil data are not presented for Northern Cone, but the relatively advanced degree of erosion at Northern Cone (Crowe et al, 1993) may indicate a relatively older age for this vent.

Clearly, the hypothesis that the Quaternary Crater Flat volcanoes erupted at resolvably different times is valid and, more importantly, a testable hypothesis given the increase in dating precision that has occurred over the last decade. Similar evidence for a relatively long-lived volcanic alignment also exists at the 0.3±0.2 Ma Sleeping Butte volcanoes (Crowe et al, 1993). Additional geochronology studies are critical to developing well-constrained eruption frequency rates used in probability calculations. Based on the limitations of the available data, the most accurate age of the Quaternary Crater Flat volcanoes is 1.2±0.4 Ma, not 1.2 Ma as reported.

It is also not clear how paleomagnetic polarity directions were sampled for this system. The Crater Flat volcanoes are described as paleomagnetically reversed, but the methods used to determine direction are not described. The procedure used to determine paleomagnetic polarities (e.g., field flux-gate magnetometer) should be discussed, along with the sampling procedure used (e.g., the number of samples per flow, the location in the flow of the sample, the number of sites per unit). These data are critical in determining if these units formed in the Matuyama reversed magnetic polarity epoch rather than the 0.92 to 1.01 Ma Jaramillo normal-polarity event (Spell and McDougall, 1992).

Recommendation: Additional geochronology studies referred to in Study Plan 8.3.1.8.5.1 should be of sufficient detail to resolve potential age differences between the Quaternary Crater Flat volcanoes. The details of the paleomagnetic direction analyses also should be presented. The Study Plan should indicate which geochronology studies are thought to be complete, and which studies are planned to resolve large uncertainties in most of the dates for Quaternary and Neogene volcanic rocks in the YMR.

References:

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Spell, T.L., and I. McDougall. 1992. Revisions to the age of the Brunhes-Matuyama boundary and the Pleistocene geomagnetic polarity timescale. *Journal of Geophysical Research* 19: 1,181-1,184.

Wells, S.G., L.D. McFadden, C.E. Renault, B.D. Turrin, and B.M. Crowe. 1990. Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: implications for the proposed high-level nuclear waste repository. *Geology* 18: 549-553.

Comment 2.2.2

Statement of Concern: Accuracy in measurements is important in all probability models, not only those based on estimates of magma flux (section 2.2.1, paragraph 4).

Basis: This paragraph reads as if the geochronology studies will only be relevant to probability models that depend on magma flux. However, geochronological data will be relevant to development and testing of all probability models of future magmatism. For example, the high-precision age data should be useful in evaluating the Poisson-Weibull models of Ho (1992).

Recommendation: This paragraph should be revised to reflect the use of geochronological data in the development and evaluation of a range of probability models.

References:

Ho, C.-H. 1992. Risk assessment for the Yucca Mountain high-level nuclear waste repository site: estimation of volcanic disruption. *Mathematical Geology* 24: 347-364.

Comment 2.2.3

Statement of Concern: (section 2.2.1, page 15, paragraph 2) It seems redundant to seek age data on 1.2 Ma basalts. Perhaps the paragraph meant that high-resolution age data are needed to resolve the volcanic history of Crater Flat.

Basis: The ages of these volcanoes are currently known with a relatively large uncertainty.

Recommendation: It would be appropriate to assign an uncertainty to the age of the Quaternary basalts in the Study Plan (i.e., 1.2 ± 0.4 Ma).

Comment 2.2.4

Statement of Concern: Will 5 to 15 samples for age determination be enough at a given volcano?

Basis: Normally 5 to 15 samples would be considered more than enough to estimate the age of volcanic activity at cinder cones. However, there are two unique problems to age determination in the YMR: (i) these volcanoes may have a complex eruptive history, (ii) different groups have collected multiple suites of rocks for age determinations already, which has led to varying reports of accuracy and precision.

Recommendation: Given this scientific need and the current controversy, it is suggested that a more systematic and detailed sampling program to be developed for individual cinder cones. A more appropriate approach may be to adopt a sampling method similar to that used to determine outcrop polarity in detailed paleomagnetic investigations, that is, establish sampling sites at individual outcrops within the same cooling unit and make seven or more age determinations at this outcrop. Then repeat this process at other stratigraphic levels. This approach may be the only reasonable one to distinguish age variations due to analytical imprecision from age variation due to polycyclic activity. Hodges (1992) suggested collecting even more samples at a given volcano in order to employ Monte Carlo statistics to determine precision. It is critical that some type of very specific sampling scheme be developed for age determinations. These data are so important that the extra time and energy expended are worthwhile, given the direct impact of these type of data on probability models.

References:

Hodges, K. 1992. Comments on volcanic issues at Yucca Mountain. *Meeting Notes* United States Nuclear Waste Technical Review Board, Panel on Structural Geology and Geoengineering, Meeting on Volcanism. September 14-16, Las Vegas, NV.

Comment 2.2.5

Statement of Concern: The accuracy of the thermoluminescence (TL) dates for the youngest soils at Lathrop Wells has not been determined in sufficient detail. How will the accuracy of these dates be determined?

Basis: Multiple analyses of nonbaked soil samples were presented in Crowe et al. (1992). The reproducibility of the dates demonstrates the precision of the technique used to obtain these values. However, there is no way to evaluate the accuracy of these dates, nor is it at all clear how the measured TL signal was acquired by the sample.

Details of the TL technique are presented in the Study Plan. Crowe et al. (1992) and this report clearly state that this technique is preliminary and has not been applied to volcanic soils. However, even the limited data presented in this report seriously question the accuracy of the dates produced through TL of unconsolidated soils.

A TL date of 24.5 ± 2.5 ka is reported in Crowe et al. (1992) for baked soil under lava Ql_3. However, other dates for members of chronostratigraphic unit 3 are three to five times older than this date. The authors state that they ". . . currently have no reasonable explanation of the age discrepancy." (Crowe et al., 1993, p. 70). A reasonable conclusion would be that although the TL technique yields fairly precise dates, the dates do not accurately reflect the age of the unit.

If the accuracy of a TL date on a baked soil is questionable, then the TL date of a nonbaked, nonconsolidated soil is even more questionable. It is practically impossible to evaluate the technique used for these TL dates, because hardly any analytical information is presented in the original data source (Crowe et al., 1992). Apparently, these samples were heated to only 100 °C to remove the least stable time signal (Crowe et al., 1992). However, it is recognized that electron traps below about 250-300 °C are unsuitable for TL dating, and that different temperature traps have different mean lifetimes (e.g., Aitken, 1978; Geyh and Schleicher, 1990). The general application of the TL technique assumes that the mean lifetime of the trap should be ten times longer than the age to be determined. Thus, determination of a roughly 10 ka age requires measuring a deep TL trap, which exists at around 300 °C (Geyh and Schleicher, 1990, p. 258). Heating to only 100 °C is insufficient to determine a 10–100 ka age, because only shallow (i.e., short lifetime) traps are activated. The TL dates presented could thus reflect the roughly 10 k.y. stability of a low temperature trap and not reflect the age of the unit.

Recommendation: Complete analytical data, including sampling techniques and glow curves, must be presented before TL dates can be taken as ages of the sampled units. Additional justification and explanation of the methodology used on the nonconsolidated soils also must be made before TL dates can be evaluated. Thus, a research plan that will clearly address the many uncertainties associated with the TL method should be devised.

References:

Aitken, M.J. 1978. Archaeological involvements of physics. *Physics Letters* C-40/5: 277-351.

Crowe, B.M., R. Morley, S. Wells, J. Geissman, E. McDonald, L. McFadden, F.V. Perry, M. Murrell, J. Porths, and S. Forman. 1992. The Lathrop Wells volcanic center: status of field and geologic studies. *Proceedings of the Third International Conference of High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 2: 1,997-2,013.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Geyh, M.A., and H. Schleicher. 1990. *Absolute Age Determination*. New York, NY: Springer-Verlag.

Comment 2.2.6

Statement of Concern: The youngest eruption at Lathrop Wells (chronostratigraphic unit 1) apparently did not modify the morphology of the cone (Crowe et al., 1993; Wells et al., 1992), yet, based on geomorphology, this unit is thought to be contemporaneous with the approximately 20 ka Black Tank cone in the Cima volcanic field. How will the age of unit 1 be resolved, using other than geomorphic data?

Basis: The youngest eruption at Lathrop Wells is the tephra exposed in the quarry south of the main cone (Crowe et al., 1993, p. 55). This tephra apparently did not mantle the main Lathrop Wells cone and thus did not exert any geomorphic control on the main cone, in contrast to the apparently young mantling eruption at Hidden Cone (Crowe et al., 1993). How can the geomorphology of the youngest Lathrop Wells eruption thus be compared with the geomorphology of the Black Tank cone?

Soil studies at the Black Tank cone do not demonstrate that chronostratigraphic unit 1 is appreciably younger (i.e., <20 ka) than the main cone at Lathrop Wells, in spite of the more youthful appearance of Lathrop Wells (Wells, et al, 1992). Crowe et al. (1993) conclude "... it is difficult and unwarranted to speculate on the extent of the time differences between the units," when referring to the different degrees of soil development between unit 3 and units 2 and 1. It is not intuitive why pedogenic features would be too indistinct to estimate the age between unit 3 and overlying units, yet would be distinct enough to distinguish <20 ka differences.

Recommendation: The age of chronostratigraphic unit 1 needs to be determined by techniques other than geomorphology. Although the pedogenic features associated with unit 1 are similar to those at Black Tank cone, it has not been demonstrated that pedogenic character can resolve ages of 20-50 k.y. difference.

References:

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Wells, S.G., L.D. McFadden, C.E. Renault, B.D. Turrin, and B.M. Crowe. 1990. Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: implications for the proposed high-level nuclear waste repository. *Geology* 18: 549-553.

2.3 Field Geologic Studies

Comment 2.3.1

Statement of Concern: The procedure used to calculate volumes of erupted basalts is unclear. Models utilizing eruptive volumes cannot be evaluated unless the methods and assumptions used to calculate volumes are more completely described. How are eruptive volumes calculated and how are existing volumes calculated?

Basis: It appears that, in the past, varying methods have been used to calculate volume data and dense rock equivalent (DRE). What method is used by Crowe et al. (1983) to calculate the volume of the cone? Assuming the cone represents a simple frustum with a basal diameter of 690 m, a crater diameter of 160 m, and a height of 140 m (Crowe et al., 1983; Crowe and Perry, 1991), Lathrop Wells has a volume of 2.2×10^7 m^3. The volume reported by Crowe et al. (1983) is 1.7×10^7 m^3, which apparently corresponds to the volume of a simple cone and would underestimate the volume of the Lathrop Wells cone. In addition, Crowe et al. (1993; Table 7.2) list the volume of Lathrop Wells as 1.4×10^8 m^3, but do not report separate cone and flow volumes.

There is no description of the methods by which magmatic volumes were calculated. Vaniman and Crowe (1981) assume that magma density is 2.7 g/cm^3, but do not state the assumed lava flow densities. Fall-deposit densities also are not reported. Cone porosities are given as 25 percent, but clast densities are presumably taken from McGetchin et al. (1974), who give a range of 1.2 to 2.8 g/cm^3 and a median of 1.5 g/cm^3. Distal scoria-fall deposits are assumed to have five times the volume of the cone, but no justification is presented for this relationship.

Recommendation: Provide a more complete description of parameters used to calculate eruption volumes and the assumptions used to convert volumes to dense rock equivalents. Describe a method for compensating for the dispersed ash associated with eruptions. Standard techniques will be important, as the Study Plan indicates that these data will be used in probability model development.

Reference:

Crowe, B.M., and F.V. Perry. 1991. *Preliminary Geologic Map of the Sleeping Butte Volcanic Centers.* Los Alamos, NM: Los Alamos National Laboratory. Los Alamos National Laboratory Report LA-12101-MS.

Crowe, B.M,, D.T. Vaniman, and W.J. Carr. 1983. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations.* Los Alamos, NM: Los Alamos National Laboratory. Los Alamos National Laboratory Report: LA-9325-MS.

McGetchin, T.R., M. Settle, and B.A. Chouet. 1974. Cinder cone growth modeled after Northeast Crater, Mount Etna, Sicily. *Journal of Geophysical Research* 79: 3,257-3,272.

Vaniman, D.T., and Crowe, B.M. 1981. *Geology and Petrology of Basalts of Crater Flat: Application to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations.* Los Alamos, NM: Los Alamos National Laboratory. Los Alamos National Laboratory Report: LA-8845-MS.

Comment 2.3.2

Statement of Concern: How will models of vent alignments be modified through further field investigations? The case has been made (Crowe et al., 1993) that basalts of the Younger Postcaldera Basalt (YPB) are part of the Crater Flat Volcanic Zone (CFVZ), NW-trending structures that provided deep-seated structural control on magma pathways, and NE-trending structures provided shallow control on location of basaltic vents in response to the maximum principal compressive stress direction of the shallow stress field. This discussion is based on the model of Crowe and Perry (1989). How will this model be tested in site characterization and how will alternative models (Smith et al., 1990) be evaluated?

Basis: Smith et al. (1990) have proposed a model incorporating the area of most recent volcanism (AMRV), which has NE-trending structures as the regional and local control for volcanism. It is not clear in the Study Plan how this alternative model will be evaluated through site characterization activities.

In addition, since the "secondary" structural control by the shallow stress field is called upon to explain the NNE alignment of cones in Crater Flat (Crowe et al., 1993), what explanation exists for control of vents by northwest structures — a situation noted at Lathrop Wells and other locations? This observation may indicate there are more complex structural controls on location of vents near Yucca Mountain that are not completely understood at present and that require further investigation.

Recommendation: It appears that current repository disruption scenarios cannot eliminate the concept of shallow, NE-trending structural control on location of igneous features. This inability means both dike intrusion through a repository and formation of a vent at the location of the repository cannot be discounted, even if probabilities are low. The relationship between dikes, vents, faults, and regional stress patterns needs to be fully addressed as part of site characterization. This assessment will have an important impact on probability models.

References:

Crowe, B.M., and F.V. Perry. 1989. Volcanic probability calculations for the Yucca Mountain site: Estimation of volcanic rates. *Proceedings for Focus '89, Nuclear Waste Isolation in the Unsaturated Zone*. La Grange Park, IL: American Nuclear Society: 326-334.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project*. Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Smith, E.I., D.L. Feuerbach, T.R. Naumann, and J.E. Faulds. 1990. The area of most recent volcanism near Yucca Mountain, Nevada: Implications for volcanic risk assessment. *Proceedings for International Topical Meeting, High-level Radioactive Waste Management*. La Grange Park, IL. American Nuclear Society: 1: 81-90

Comment 2.3.3

Statement of Concern: Several inconsistencies exist in the geologic map and stratigraphic relationships at Lathrop Wells. Although it is not the intent of the Study Plan to present data, these inconsistencies are pointed out in the hope that future mapping will resolve them.

Basis: Inconsistencies in stratigraphic relationships at Lathrop Wells are identified below by page number in Crowe et al. (1993). Future site characterization activities should work toward resolution of these inconsistencies.

p. 45: What is the location of site QE? Unit Qs_{4a} contains an internal contact by the dendritic lobes immediately up from the main Qs_{4a} scoria mounds.

p. 46: Champion (1991) does not provide sample numbers or sample sites. However, Figure 2 of Turrin and Champion (1991) shows samples NNTS #5-86 in unit Ql_5, B8203, 211-1 and B8191 in unit Qs_5. Unless sample locations and magnetic data are reported, there is no way to evaluate the lack of correlation between unit Ql_5-Qs_5 and the eastern fissure unit Qs_{2b}.

p. 50: Unit Qs_{2c} is supposedly exposed "north and northeast of the main cone," but there is no Qs_{2c} shown northeast of the cone on the map in Figure 2.9. Do the deposits "northeast of the main cone" refer to the surge deposits that underlie unit Ql_3 (i.e., to the northeast) and may be correlative with Qs_{2c}, or are there additional small exposures of unit Qs_{2c} that are not mapped? In contrast, elsewhere on page 50 it states that subunit Qs_{2c} crops out extensively **northwest** and **west** of the main cone, which is apparently shown in Figure 2.9. The following paragraph states that "the thickest accumulations of the pyroclastic surge deposits occur **north** and northwest of the main cone."

p. 51: The pyroclastic surge unit (Qs_{2c}) overlying Ql_{4b} lava lacks carbonate coatings, which is inferred to indicate a time break between deposition of these units. Would carbonate coatings necessarily form at the same rate on these two units, given the differences in porosity, permeability, and composition? In addition, are carbonate coatings developed on any of the overlying unit 2 scoria deposits? This argument needs to be supported by data.

p. 53: No basis is provided for concluding that the erosional unconformity between units Qs_{4b} scoria and the main cone scoria represents "at least a few tens of thousands of years." The ^3He dates on the cone only yield a minimum age of the main cone of 44 ± 5-6 ka. The age of unit Qs_{4b} has not been determined directly, but it likely corresponds in age to unit Qs_{4a}, which has a preliminary U/Th date of 150 ± 40 ka. However, the ^3He dates on lava Ql_4 are 48 ± 5 and >49 ka (Crowe et al., 1992; Poths and Crowe, 1992) and are thus contemporaneous with the main cone. Poths and Crowe (1992) also conclude that the scoria cone might be as old as the lavas (units Ql_5, Ql_4, and Ql_3). These data do not support the conclusion that this unconformity represents "at least a few tens of thousands of years."

Recommendation: Correct minor errors on geologic map of Lathrop Wells. Clarify apparent stratigraphic discrepancies that exist between map and text in Crowe et al. (1993). Future mapping activities described in the Study Plan should work toward resolution of these specific issues.

References:

Champion, D.E. 1991. Volcanic episodes near Yucca Mountain as determined by paleomagnetic studies at Lathrop Wells, Crater Flat, and Sleeping Butte, Nevada. *Proceedings of the Second International Conference of High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 61-67.

Crowe, B.M., R. Morley, S. Wells, J. Geissman, E. McDonald, L. McFadden, F.V. Perry, M. Murrell, J. Porths, and S. Forman. 1992. The Lathrop Wells volcanic center: status of field and geologic studies. *Proceedings of the Third International Conference of High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 2: 1997-2013.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Poths, J., and B.M. Crowe, 1992. Surface exposure ages and Noble gas components in volcanic units at Lathrop Wells volcanic center, Nevada. *Eos, Transactions of the American Geophysical Union* 73: 610.

Turrin, B.D., and D.E. Champion, 1991. $^{40}Ar/^{39}Ar$ laser fusion and K-Ar ages from Lathrop Wells, Nevada, and Cima, California: the age of the latest volcanic activity in the Yucca Mountain area. *Proceedings of the Second International Conference of High-Level Radioactive Waste Management.* La Grange Park, IL: American Nuclear Society: 68-75.

Comment 2.3.4

Statement of Concern: Crowe et al. (1993, p. 104) contend that strain rates have decreased since Miocene. There may be an important relationship between strain and magmatism. How will geodetic data be incorporated into volcanological site characterization?

Basis: If Crater Flat Valley is interpreted as a pull-apart, intrusion or eruption processes may be directly influenced by the strain rate. The contention that strain rates have decreased since the Miocene is probably true (Crowe et al., 1993), but that inference is based on decreased average slip rates on the Yucca Mountain faults. Regional strains may still be significant, but slip may be localized on faults such as Death Valley-Furnace Creek, Bare Mountain, etc. The Crater Flat Valley pull-apart would still experience extension that may localize magmatism. The Little Skull Mountain earthquake is an indication that the area is still extending.

Recommendation: Describe how measurements of contemporary strain may be acquired and used to support this contention.

References:

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

2.4 Geochemistry

Comment 2.4.1

Statement of Concern: No mention is made of how the phenocryst mineralogy will be characterized in sparsely phyric rocks.

Basis: The examination of thin-sections alone is inadequate to characterize the presence or absence of low-abundance minerals in volcanic scoria (e.g., Chayes, 1956). Additional mineralogical analyses are not listed in the Study Plan, with the exception of thin-section petrography. Unless detailed heavy-mineral separations are performed on these units, the presence of amphibole in some or all of the Quaternary cannot be discounted.

Phenocrysts of amphibole occur in the NE Little Cone scoria (Vaniman and Crowe, 1981), the Sleeping Butte cones (Crowe et al., 1983), and that at least some Red Cone units contain groundmass(?) amphibole and biotite (Vaniman and Crowe, 1981; Ho et al., 1991). The presence of amphibole phenocrysts has critical implications for eruption dynamics models. The only detailed petrographic data reported for 4 Ma and younger basalts is by Vaniman and Crowe (1981). These data are inadequate to evaluate the mineralogy and phase relationships of these units. Petrographic data are presented without any description of the methods used to determine mineral abundances, nor are uncertainties in mineral abundances described. Detailed petrographic data have not been presented for Buckboard Mesa flows. Lathrop Wells petrographic data are reported as vesicle-free abundances, yet vesicle abundances are not listed (Vaniman and Crowe, 1981). Data presented in Zreda et al. (1993) and Crowe et al., (1993) indicate that plagioclase is a phenocryst in Lathrop Wells unit Ql_6 and perhaps unit Ql_4, but plagioclase is not reported in Vaniman and Crowe (1981). The presence of plagioclase phenocrysts is critical to the arguments for increasing source depth with time in the Crater Flat magma system.

Recommendation: Detailed petrographic studies should be performed to more accurately and precisely determine the mineralogy of the younger post-caldera basalt suite, because the presence or absence of amphibole has important implications for the volatile content and, thus, explosivity of an eruption. Detailed heavy-mineral separations are required to determine the presence or absence of amphibole in these units. Additional matrix-mineral separations also are needed to determine the presence of plagioclase phenocrysts, which were not detected at Lathrop Wells in earlier studies. This determination will be important in constraining consequence models, as water content may be constrained using phenocryst assemblages and because phenocryst size and abundance will influence magma viscosity.

References:

Chayes, F. 1956. *Petrographic modal analysis.* New York, NY: John Wiley & Sons.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project.* Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory: 326 pp.

Crowe, B.M,, D.T. Vaniman, and W.J. Carr. 1983. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations.* Los Alamos, NM: Los Alamos National Laboratory. Los Alamos National Laboratory Report LA-9325-MS.

Ho, C.-H., E.I. Smith, D.L. Feurbach, and T.R. Naumann. 1991. Eruptive probability calculation for the Yucca Mountain site, USA: Statistical estimation of recurrence rates. *Bulletin of Volcanology* 54: 50–56.

Vaniman, D.T., and Crowe, B.M. 1981. *Geology and Petrology of Basalts of Crater Flat: Application to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations.* Los Alamos, NM: Los Alamos National Laboratory. Los Alamos National Laboratory Report: LA-8845-MS.

Zreda, M.G., F.M. Phillips, P.W. Kubik, P. Sharma, and D. Elmore. 1993. Cosmogenic ^{36}Cl dating of a young basaltic eruption complex, Lathrop Wells, Nevada. *Geology* 21: 57-60.

Comment 2.4.2

Statement of Concern: There is no discussion in this Study Plan of the xenolith content of the Lathrop Wells cinder cone or other cinder cones in the region, or how xenolith abundances will be studied to better characterize volcanism and constrain consequence models. The abundance, size distribution, morphology, and composition of xenoliths in the Lathrop Wells ejecta have critical implications for eruption consequence models, yet published data are inadequate to constrain those models.

Basis: Xenolith abundances directly reflect the ability of the fragmented magma to transport brecciated wall rock to the surface. Consequence models of potential volcanic eruptions through the Yucca Mountain repository horizon will need to constrain the ability of a basaltic dike to fragment and transport to the surface both wall rock and waste canisters. The abundances, origins, and size distributions of shallow (i.e., < 1 km) crustal xenoliths are thus critical to developing realistic consequence models.

Xenolith data for Lathrop Wells have been reported by Crowe et al. (1983) and Crowe et al. (1986). However, these data are inadequate to accurately characterize the process leading to xenolith formation and transport during this eruption. Crowe et al. (1983) state that thin-section examination of an unstated number of xenoliths shows that ". . . the fragments are probably derived entirely from the Tiva Canyon Member of the Paintbrush Tuff . . .," but the criteria used to make that determination are not described. In addition, the only reference to the size of the xenoliths at Lathrop Wells is that they have a median diameter of 4 mm (Crowe et al., 1983). Field examination of the Lathrop Wells cinder cone reveals that tuffaceous xenoliths much greater than 4 mm are extremely common, and tuffaceous xenoliths in the centimeter to decimeter range occur in unusual abundance relative to other Basin and Range cinder cones.

The only granulometric data that identify clast composition in the Lathrop Wells cone is in Crowe et al. (1986). However, these data are only for clasts <0.7 mm, and xenolith composition is generally described as undifferentiated with only occasional identification of tuff or limestone clasts (Crowe et al., 1986, Appendix F). The bulk of the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff are compositionally zoned and sparsely phyric, containing very similar mineralogies (U.S. Department of Energy, 1988). The only apparent distinction is that the Tiva Canyon contains trace phenocrysts of sphene, which are absent in the Topopah Spring (U.S. Department of Energy, 1988). It is not at all clear how submillimeter, sparsely phyric tuff or undifferentiated xenoliths were uniquely assigned to the Tiva Canyon Member of the Paintbrush Tuff by Crowe et al. (1983). In addition, the occurrence of limestone xenoliths in the Lathrop Wells scoria (Crowe et al., 1983) clearly indicates that pre-tuff limestone units were entrained during the eruption.

Recommendation: Additional studies of the abundance, size distribution, morphology, and composition of xenoliths in the Lathrop Wells ejecta are needed in order to construct realistic models of fragmentation and transport of subsurface material. It appears that few xenolith data will be collected to constrain eruption mechanics models.

References:

Crowe, B.M., S. Self, D. Vaniman, R. Amos, and F.V. Perry. 1983. Aspects of potential magmatic disruption of a high-level nuclear waste repository in southern Nevada. *Journal of Geology* 91: 259-276.

Crowe, B.M., K.H. Wohletz, D.T. Vaniman, E. Gladney, and N. Bower. 1986. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations*. Los Alamos, NM: Los Alamos National Laboratory. Los Alamos National Laboratory Report LA-9325-MS.

U.S. Department of Energy. 1988. *Site Characterization Plan*. DOE/RW-0160. Washington, DC: U.S. Department of Energy: I, Chapter 1.

Comment 2.4.3

Statement of Concern: It appears that few data will be collected to constrain hydrothermal activity models that likely occurred at Lathrop Wells and other cinder cones in the region after the eruption of these basalts. This lack of data may be important because the volumes of rock affected by diffuse degassing may be much larger than the volumes of rock affected by direct disruption. Therefore, degassing and hydrothermal alteration should be assessed and considered in probability models.

Basis: Volatile concentration in magmas and interaction with shallow groundwater are important parameters that govern eruption mechanics. After the cessation of eruptive activity, heat and mass transfer to the surface and through rock surrounding shallow intrusions continues through convective degassing and heat conduction. This type of degassing activity may have an important impact on repository performance in several ways. First, direct effects of volcano degassing include the movement of gas through the repository block itself. This activity may result in accelerated rates of container corrosion and deterioration of the waste package itself. Direct effects of volcano degassing would likely accompany direct magmatic disruption of the repository, but also could occur if magma intruded rocks near the repository, without actually intersecting the repository itself. Therefore, the probability of this type of activity occurring is higher compared to the probability of direct magmatic disruption. Second, indirect effects of degassing may also impact repository performance. Indirect effects may include change of partitioning of radionuclides between aqueous and solid phases, and changes in sorption of radionuclides. Finally, change in movement of groundwater and gas phases in the geologic environment, and changes in the mechanical properties of the rock, also may result from degassing and thermal loading of rock by conductive and convective heat transfer. All these possible effects raise compliance issues.

The effects of degassing on repository performance are different from those associated with eruptive activity for the following reasons.

- Volcanic degassing is a long-term process. Preliminary data from Parícutin, Tolbachik, and Cerro Negro indicate that cinder cones generally cool and degas over long periods of time. Vigorous, high-temperature degassing persists at some cinder cones for decades. Low-temperature and less vigorous degassing may continue for more than 100 years. Low-temperature fumaroles are found at Jorullo volcano, Mexico, for example, more than 200 years after that volcano's eruption (J.F. Luhr, pers. comm., 1992).

- Volcanic degassing is capable of influencing an area much greater than is disrupted by eruptive activity. This area of influence is important because most probability models for volcanic activity are area dependent; the probability of volcanic gases interacting with the repository and surrounding geological environment is much higher than the probability of direct disruption by magma transport.

- Volcanic degassing does not result in the fragmentation, transport, or dispersion of rock and repository waste, as direct disruption of magma would. Instead, volcanic degassing has long-term effects on the geochemistry of the repository and surrounding rock. Volcanic gases are generally acid solutions, with pH in the range of 0.1 to 2. Gas temperatures commonly range from magmatic (800 to 1000 °C) near vents to ambient far from vents. Dominant species in the gases are water, carbon dioxide, sulfur dioxide, hydrogen chloride, dihydrogen sulfide, and trace compounds, including trace metals like mercury and noble gases. Because of their composition, influx of volcanic gases into the repository would accelerate corrosion of waste containers, alter transport rates in the geologic environment, and alter the mechanical strength of the rocks in and around the repository block. These effects are different from simple thermal loading, such as that resulting from the repository itself, because in addition to enhanced thermal effects, mass flow of volcanic gases through the geologic environment will occur.

Because of these possible effects, it is important to attempt to constrain the areas affected by diffuse degassing in the YMR through mapping of alteration zones within cinder cone edifices and around cinder cones.

Recommendation: Map the alteration zones around Lathrop Wells and other YMR cinder cones in detail and devise an approach for evaluating the extent of alteration and diffuse degassing about these volcanoes shortly after their period(s) of activity.

2.5 Evolutionary Cycles of Basaltic Fields

Comment 2.5.1

Statement of Concern: Volumetric relationships are vastly different in volcanic systems in western North America. How will these relationships be used specifically to develop time-dependent, volume-predictable models for the Crater Flat system?

Basis: Magma systems along the Colorado Plateau transition area certainly have higher eruption rates than Western Great Basin (WGB) systems, but it is not clear how analogous these two areas are. They have very different tectonic environments and histories, along with distinct petrogenetic trends (e.g., Fitton et al., 1991). Crater Flat is a small volume system, yet there are numerous other late Cenozoic, small-volume Basin and Range-WGB systems such as the Death Valley, Mono Lake, Seven Troughs, Winnemucca, Battle Mountain, Table Mountain, Monarch Divide, Candellaria, Kern, Greenwater, Fallon, Tahoe, and Saline Range (Smith and Luedke, 1984) that may be more analogous to the YMR than, say, the Springerville field. Although volumetric data are not readily available for most of these areas, this lack of data does not mean that these areas should be excluded from consideration. The Crater Flat system certainly is small relative to Colorado Plateau transition systems, yet it may not be anomalously small relative to other WGB systems.

Recommendation: Hypotheses regarding volumetric relationships in the Crater Flat system need to be made so as to explore potential relationships with poorly studied, yet relatively analogous WGB mafic volcanic systems.

Reference:

Fitton, J.D., D. James, and W.P. Leeman. 1991. Basic magmatism associated with late Cenozoic extension in the western United States: compositional variations in space and time. *Journal of Geophysical Research* 96: 13,693-13,711.

Smith, R.L., and Luedke, R.G. 1984. Potentially active volcanic lineaments and loci in the western conterminous United States. *Reviews in Geophysics*. Washington, DC. National Academy Press: 47-66.

Comment 2.5.2

Statement of Concern: Crowe and Perry (1989) use a decrease in magma volume with time at the Springerville Volcanic Field to support the hypothesis that the CFVZ is a waning system. However, large petrogenetic changes and two orders-of-magnitude more basalt are present in the Springerville system which indicates this system may not be truly analogous to the CFVZ. How will analogy be established between the Springerville field and other volcanic fields and those of the WGB?

Basis: The gradual change to smaller eruptive volumes in Springerville at about 1 Ma is accompanied by a change in magma composition from tholeiitic to alkalic (Condit et al., 1989; Cooper and Hart, 1990). This trend is thought to represent a shift from lithospheric to more asthenospheric mantle sources. Similar compositional trends are not observed in the CFVZ within the last 4 Ma (Crowe et al., 1993). The Springerville field erupted around 300 km^3 of mafic rock, but less than 1 km^3 has been erupted in the CFVZ since about 3.7 Ma (Crowe and Perry, 1989). The dynamics of magma generation, ascent, and eruption may be extraordinarily different for volcanic fields with such different magma fluxes.

Recommendation: Develop criteria for selecting analogous areas with reference to tectonic setting and paragenesis of magmas. These criteria should be evaluated for each field and discussed in terms of the utility of models developed in these areas for evaluating Yucca Mountain during site characterization.

References:

Condit, C.D., L.S. Crumpler, J.C. Aubele, and W.E. Elston. 1989. Patterns of Volcanism Along the southers Margin of the Colorado Plateau: The Springerville Field. *Journal of Geophysical Research*. 94: 7,975-7,986.

Cooper, J.L., and W.K. Hart, 1990. Mantle sources in the Arizona transition zone and global mantle heterogeneity. *Geology* 18: 1,146-1,149.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project. Los Alamos National Laboratory Report: Los Alamos National Laboratory: Los Alamos: NM: 326 pp.

Crowe, B.M., and F.V. Perry. 1989. Volcanic probability calculations for the Yucca Mountain Site: estimates of volcanic rates. *Proceedings, Nuclear Waste Isolation in the Unsaturated Zone, Focus '89.* La Grange Park, IL: American Nuclear Society: 326-334.

Comment 2.5.3

Statement of Concern: Current models of temporal and spatial variations in parental basalt composition focus on changes in depth of the source, and do not consider widely recognized compositional changes in the mantle (Crowe et al., 1993). These models have been used to conclude that the Crater Flat system is waning. Regional geochemical trends indicate that the WGB system, which includes the YMR, may continue activity for several million years, whereas contemporaneous nonWGB systems may be wanning in activity. How will the research discussed in this Study Plan be used to resolve alternate petrogenetic models?

Basis: The conclusion that observed temporal trends in the Great Basin from tholeiitic to alkalic magmatism are produced exclusively by progressively lower degrees of mantle melting at "greater depths" (Crowe et al., 1993) is misleading, and ignores important differences in mantle composition that occur with this trend. The hypothesis that alkalic basalt can be derived through smaller degrees of mantle melting than occurs during the formation of tholeiitic magma has well-developed empirical (e.g., Gast, 1968) and experimental evidence. However, this argument is generally applied to systems such as Hawaii, where the mantle is of relatively uniform composition and has not been modified by metasomatic processes (e.g., Frey et al., 1978).

Isotopic and trace element studies (e.g., Perry et al., 1987; Farmer et al., 1989; Fitton et al., 1991; Kempton et al., 1991) have shown that asthenospherically derived melts in the Basin and Range (BR) have had variable amounts of interaction with metasomatized lithospheric mantle. The observed transition to more undersaturated compositions in the BR at about 5 Ma occurs with large geochemical and isotopic changes that clearly show different parental mantle compositions (i.e., less lithospheric character for <5 Ma basalts). Such changes are inconsistent with deriving these magmas from the same mantle source by simply varying the amount or depth of partial melting. Similar transitions from lithospheric to non-lithospheric character are less clearly developed for volcanic systems around the Colorado Plateau, such as the Springerville volcanic field (Fitton et al., 1991). Although Condit et al. (1989) hypothesize that smaller amounts of partial melting occurred during the late, alkalic stage of Springerville magmatism, they clearly state that this transition is accompanied by a shift from a lithospheric to an asthenospheric source for the magmas. Isotopic studies by Cooper and Hart (1990) also show a complex transition between lithospheric and asthenospheric mantle signatures in the Springerville system. Thus, even when a transition to more undersaturated compositions is observed, the mantle source changes from metasomatized lithosphere to oceanic island basalt-type asthenosphere. The Study Plan does not indicated how differences in mantle composition, and not degrees of mantle melting, can affect regional petrogenic trends.

In contrast to the central BR system, these temporal shifts to more undersaturated compositions at about 5 Ma are not observed in the WGB. Volcanic fields such as Crater Flat, Coso, Big Pine, Death Valley, and Mono Lake clearly show a lithospheric source for both pre- and post-5 Ma rocks (Fitton et al., 1991; Farmer et al., 1989). This Study Plan and Crowe et al. (1993) combine the WGB with the main BR system, and thus make erroneous interpretations regarding compositional shifts with time. This temporal relationship is important because the contention that alkaline magmatism in the WGB field indicates a waning system is not consistent with observed temporal trends throughout the central BR and Colorado

Plateau margin systems. The WGB systems have yet to evolve from a lithospheric to an asthenospheric phase of activity. Cima and the Lunar Crater volcanic fields are nonWGB magma systems that show a transition from lithospheric Pliocene alkaline basalt to compositionally distinct asthenospheric Quaternary alkaline basalt (Crowe et al., 1986; Wilshire et al., 1991; Foland and Bergman, 1992; Crowe et al., 1993). This relationship shows that activity can continue for millions of years after inception of asthenospherically derived magmatism. The Crater Flat system has yet to reach an asthenospheric stage of magmatism (Vaniman et al., 1982; Farmer et al., 1989), and thus cannot be considered a waning magma system on the basis of regional petrogenetic trends.

Modification of WGB and other allied BR systems by crustal contamination is another possible hypothesis to explain regional petrogenetic trends. Glazner et al. (1991) presented data for the Amboy-Pisgah volcanic centers that contamination by mafic crust could produce some of the geochemical variability in the magma system. The hypothesis that crustal contamination could control some of the geochemical variation observed in the Crater Flat system has not been examined in detail by previous studies. The methodologies outlined in the Study Plan emphasize mantle processes and apparently ignore crustal interaction hypotheses.

Recommendation: Changes in source composition need to be incorporated into regional petrogenetic models. Regional interpretations of waning magmatism need to be supported by comparison to analogous systems in the WGB, not to systems in the BR or BR-transition zone. Several alternative hypotheses besides waning magmatism are viable for WGB systems, and remain to be tested. It is recommended that geochemical studies in the YMR and in other "analogous" fields consider these complexities.

References:

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3 SUMMARY

Study Plan 8.3.1.8.5.1 covers important areas of investigation. Results of this site characterization process should improve probability and consequence models for volcanism. All facets of the proposed investigation described in the Study Plan should be carried out as a part of the DOE program of site characterization in order to determine compliance. However, the Study Plan is not specific about how certain investigations will be carried out, or how alternative models will be investigated as part of the on-going site characterization process. Furthermore, some areas of investigation that will be critical to the development of PA models and determination of compliance are not addressed by the Study Plan.

Several important aspects of site characterization are intended to resolve issues related to the probability of magmatic disruption of the repository. It is unclear how investigations proposed in this Study Plan can be used to resolve important questions related to probability model development, or the testing of alternative probability models. Geophysical investigations could provide important constraints on probability models. These geophysical investigations include: (i) ground magnetic surveys, and possibly electrical surveys, for the purpose of identifying shallow dike sets in the alluvium along the Crater Flat volcano alignment, and (ii) passive or active high-resolution seismic tomography surveys of the YMR. These surveys will delineate slow velocity zones in the middle to shallow crust, which have indicated the presence of magma bodies in other similar volcanic areas. High-resolution geophysical data also may be useful for delineating the relationship between faults and dikes in some parts of the YMR. In the past, it has been difficult to integrate geophysical and volcanological data sets. Therefore, it seems appropriate that some of these detailed surveys be described explicitly as part of site characterization activities related to volcanism.

These data will likely be very useful for differentiating between alternative probability models. For example, it only may be possible to differentiate between models of deep structural control on the CFVZ (Crowe et al., 1993) and NE-trending structural models (Smith et al., 1990) through the application of integrated geophysical, structural, and volcanological surveys. The Study Plan should describe in specific terms how these activities will be linked to resolve probability issues. As currently written, it appears that important data will not be collected or will not be integrated at an early stage into volcanological studies.

It is not clear from the Study Plan how geochemistry and physical volcanological analyses will be used to improve consequence modeling. Geochemical and physical volcanological studies in site characterization must focus on problems related to eruption mechanics and secondary effects of volcanism, in addition to investigations related to magma petrogenesis and the development of volume-predictable models. Areas in which this study can be done include characterization of magma rheology, xenolith concentration and depth of origin, phenocryst mineralogy, abundance, size, and distribution, and study of hydrothermal alteration within and near cinder cones. This Study Plan does not describe how these data will be collected, despite the fact that this information is important to understanding the consequences of volcanic activity (Trapp and Justus, 1992; Crowe et al., 1993).

Finally, it is important that the Study Plan describe the methods used to determine the suitability of using other fields as analogs for specific aspects of YMR volcanism. For example, the Springerville field may provide important insight into some aspects of YMR volcanism, such as the relationship between vent alignments, structure, and tectonic stress patterns (Connor et al., 1992), but there are important differences in petrogenesis between Springerville (Condit et al., 1989) and YMR volcanism that likely limit the utility of Springerville as an analog for volume-predictable models. The Study Plan should provide specific details about the context in which analogs will be used.

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