CNWRA 95-002

EXPERT-PANEL REVIEW OF CNWRA VOLCANISM RESEARCH PROGRAMS

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

January 1995
Revised March 1995

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ABSTRACT

An independent panel of five experts in basaltic volcanology reviewed ongoing volcanism research programs at the Center for Nuclear Waste Regulatory Analyses (CNWRA). The goals of this review were to (i) critically review the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain high-level waste repository site; (ii) recommend improvements to the research scope and methodologies, and investigate new issues that may not be part of the original research plans; and (iii) evaluate interpretations of the available data and explore alternative hypotheses. The panel members reviewed all CNWRA volcanism documents, attended a 2-day meeting in San Antonio and examined Yucca Mountain region (YMR) basaltic volcanoes in the field for 2 days. The main conclusions of the review are: (i) CNWRA volcanism research projects are using scientifically defendable methods, relevant to addressing important geological problems at the YMR, and are being undertaken by well-qualified personnel; (ii) CNWRA studies of basaltic volcanism in the YMR should be increased, including Miocene basaltic activity associated with waning stages of caldera magmatism; (iii) physical volcanological studies of Quaternary YMR basaltic volcanoes should be conducted and these studies supplemented with data from other appropriate Basin and Range and modern analog volcanoes; (iv) evaluation of the relationships between YMR and modern analog volcanoes should be continued as data from planned CNWRA studies become available; (v) project goals should be prioritized to focus on the most urgent tasks; and (vi) more time should be allocated for in-depth studies that result in peer-reviewed journal publications.

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ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research, Division of Regulatory Applications. This report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

Aaron DeWispelare provided valuable guidance for the expert-panel elicitation process, which enabled the formation of an independent review panel. Charles Connor was instrumental in preparing for the review meetings and leading many discussions during the meetings. Cathy Garcia provided crucial logistical support for the review meeting, in addition to her assistance in the preparation of this report. Technical reviews by H. Lawrence McKague, Aaron DeWispelare, and Budhi Sagar along with editorial reviews by James Pryor greatly improved the content of this report.

1 INTRODUCTION

1.1 BACKGROUND

The Yucca Mountain region (YMR) has been the site of recurring basaltic eruptions during the last 8 million years (Vaniman et al., 1982; Smith et al., 1990). This volcanic activity has led to the formation of numerous cinder cones, six of which are less than 1.6 million years old and located within 20 km of the candidate repository site. Because of this igneous activity, it is necessary to evaluate the potential for volcanic disruption of the candidate high-level radioactive waste repository at Yucca Mountain (i.e., 10 CFR 60.122, Nuclear Regulatory Commission, 1991).

The probabilities and potential consequences of igneous activity on repository performance are the subject of considerable debate. Current research shows, however, that the probability of igneous activity at the candidate repository site is greater than 1×10^{-4} in 10^4 years (e.g., Connor and Hill, 1993; Crowe, 1994). Ongoing research also demonstrates that basaltic volcanoes in the YMR likely represent a range of eruptive activity, which can produce different effects on repository performance. Highly explosive eruptions are capable of fragmenting and entraining significant amounts of wall rock, and transporting that material tens to hundreds of kilometers away from the vent (e.g., Amos et al., 1983; Fedotov, 1983; Crowe et al., 1986). Conversely, relatively gentle effusions of magma from fissure-fed eruptions may produce very limited disruption and dispersal of subsurface material (e.g., Vaniman and Crowe, 1981; Valentine et al., 1992; Barr et al., 1993). These probability and consequence models will need to be evaluated in detail as part of prelicensing and licensing activities.

Volcanism research independent of U.S. Department of Energy (DOE) activities is necessary to support specific sections of the License Application Review Plan (LARP). Insight into the frequency, distribution, and volume of basaltic magmatism in the YMR, the repository and regional scales of volcanism effects, and the relationship between volcanism and regional tectonic and structural settings, forms an integral part of site characterization activities (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 the description of overall system performance (Assessment of compliance with the requirement for cumulative releases of radioactive materials, LARP Section 6.1). The Compliance Determination Strategy (CDS) associated with evidence of Quaternary volcanism is of Type 5, indicating that Nuclear Regulatory Commission (NRC) must conduct independent research to evaluate Key Technical Uncertainties (KTUs) associated with volcanism and that volcanism poses a high risk to the NRC of reaching unwarranted conclusions regarding compliance with 40 CFR Part 191 (U.S. Environmental Protection Agency, 1991) and 10 CFR Part 60.122(c)(15) (Nuclear Regulatory Commission, 1991).

Four KTUs related to igneous activity, identified as part of the CDS concerned with evidence of Quaternary igneous activity, have been identified:

- 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

- Prediction of future system states (disruptive scenarios)

These KTUs currently are being re-evaluated. The first two KTUs likely will be combined into a single KTU that focuses on the inability to directly sample many past and present features of igneous activity. A new KTU also is being considered that addresses the lack of direct analogs for magmatic effects on repository performance. The justification for this KTU is that models for these magmatic effects will be difficult to evaluate, and that magma interaction with undisturbed wall rock at 300 m is not a good analog for possible magmatic effects on repository performance. Regardless of the integration efforts, KTU evaluation requires detailed safety review supported by analyses (Type 4) and independent tests and other investigations (Type 5). In addition to KTU evaluation, independent research in volcanism is needed by the NRC to provide a basis to question how DOE research will address the probabilities and potential consequences of igneous activity on repository performance and to evaluate the DOE responses to these questions.

Two volcanism research projects are ongoing at the Center for Nuclear Waste Regulatory Analyses (CNWRA) to investigate issues related to igneous activity KTUs and to provide a solid technical basis for the overall review of the DOE license application. The Volcanic Systems of the Basin and Range Project (VSBR) (Stirewalt et al., 1994) is designed to: (i) assess the probability of continued magmatic activity in the YMR; (ii) evaluate the quality, quantity, and uncertainties associated with volcanological data in the YMR and nearby volcanic fields; and (iii) develop models that better predict the interaction between crustal tectonics and volcanism. The Field Volcanism Project (FV) (Connor and Hill, 1994) focuses on characterizing the potential consequences of igneous activity on repository performance through investigations of the: (i) mechanics of basaltic cinder cone eruptions, (ii) extent and characteristics of shallow hydrothermal systems and diffuse degassing associated with basaltic eruptions, and (iii) nature of basaltic intrusive geometries at repository depths.

1.2 REVIEW OBJECTIVES

The CNWRA is committed to providing the NRC with the highest possible quality technical assistance and research products. External peer reviews of ongoing research projects provide a mechanism to ensure that scientifically defendable research is being conducted. Because of the controversies surrounding many YMR volcanism issues, an external review of the CNWRA volcanism research projects was desired. The primary goals of this review were to:

- Critically review the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain high-level waste (HLW) repository site

- Recommend improvements to the research scope and methodologies and identify new issues for investigation that may not be part of the original research plans

- Evaluate interpretations of the available data and explore alternative hypotheses

The overall emphasis of the review is to provide individual recommendations on the CNWRA volcanism research. The review was not designed to arrive at a panel consensus nor to resolve YMR scientific controversies. Actions recommended by CNWRA in Section 3.2 of this report for modifying volcanism research in response to the peer reviewers' comments require further discussion with and possible modification by the NRC staff before they are implemented in the volcanism research projects.

2 REVIEW METHODS

There is no completely objective procedure to select experts for a review panel. Research in basaltic volcanism can involve a wide range of scientific disciplines and specialties, all of which cannot be equally represented on a review panel. The CNWRA volcanism research projects emphasize five major disciplines in volcanology that include: (i) basaltic volcanism of the Basin and Range Province, (ii) dynamics of basaltic eruption processes, (iii) volcanic heat and mass-transfer processes, (iv) probability modeling in volcanic fields, and (v) petrology of basaltic systems. Thus, experts from these volcanological disciplines were needed for the review panel.

A self-selection process is the most objective yet practical method to form a review panel (e.g., DeWispelare et al., 1993; 1994). This process involves soliciting nominations from recognized experts in the appropriate field as to whom they would nominate for a review panel. These nominations are compiled, and provided selection criteria are met (e.g. scientific discipline representation, free of conflict of interest, etc.), the leading nominees are invited to join the review panel.

For the CNWRA volcanism research review, an initial letter soliciting nominations for review panel membership (Appendix A) was sent to 72 active researchers in basaltic volcanology, beginning in late May 1994. These researchers are employed at United States and international academic institutions, the U.S. Geological Survey (USGS), private and governmental research laboratories, and as editors of peer-reviewed journals. The only restrictions placed on the nominations were that present and former CNWRA consultants and employees of the DOE were ineligible for panel membership, due to possible conflicts of interest. Five to ten nominations from the appropriate volcanism disciplines were requested. Based on responses to these letters, 78 additional solicitation letters were sent in June 1994 to researchers nominated by the first group. There was a 64-percent response rate to the solicitation letters, which resulted in the nomination of 212 potential review-panel candidates. Respondents who indicated an interest in participation on the review panel were sent additional information about the review. Respondents that were unavailable to participate on the review panel were thanked for their nominations and assistance. The last response to the nomination letters was received in early August 1994.

The distribution of the number of nominations that each candidate received is shown in Figure 2-1. Four of the five expert-panel candidates received the highest number of nominations among respondents expressing an availability and interest in participating on the review panel. Fortuitously, these panel candidates each had different research emphases in volcanology, which were consistent with the emphases in the CNWRA volcanism research projects. The fifth panel candidate received the highest number of nominations for his discipline. Although several other people had more nominations, their research emphases were in disciplines already represented by the leading nomines.

The five leading candidates for the review panel were sent letters of invitation (Appendix B) and an outline of the proposed review (Appendix C). All the candidates accepted the invitation to participate on the review panel and were hired as CNWRA consultants for this review. The expert-panel members were, in alphabetical order:

- Dr. Paul Delaney, USGS, Flagstaff, Arizona. Dr. Delaney's research for the past 14 yr has focused on a wide range of topics, including heat and mass transfer processes in volcanic systems, geodetic studies at active volcanoes, and magma ascent and emplacement mechanics. He has published over 30 papers on these topics, and he is a highly nominated reviewer for about 20 journal articles and research proposals each year.

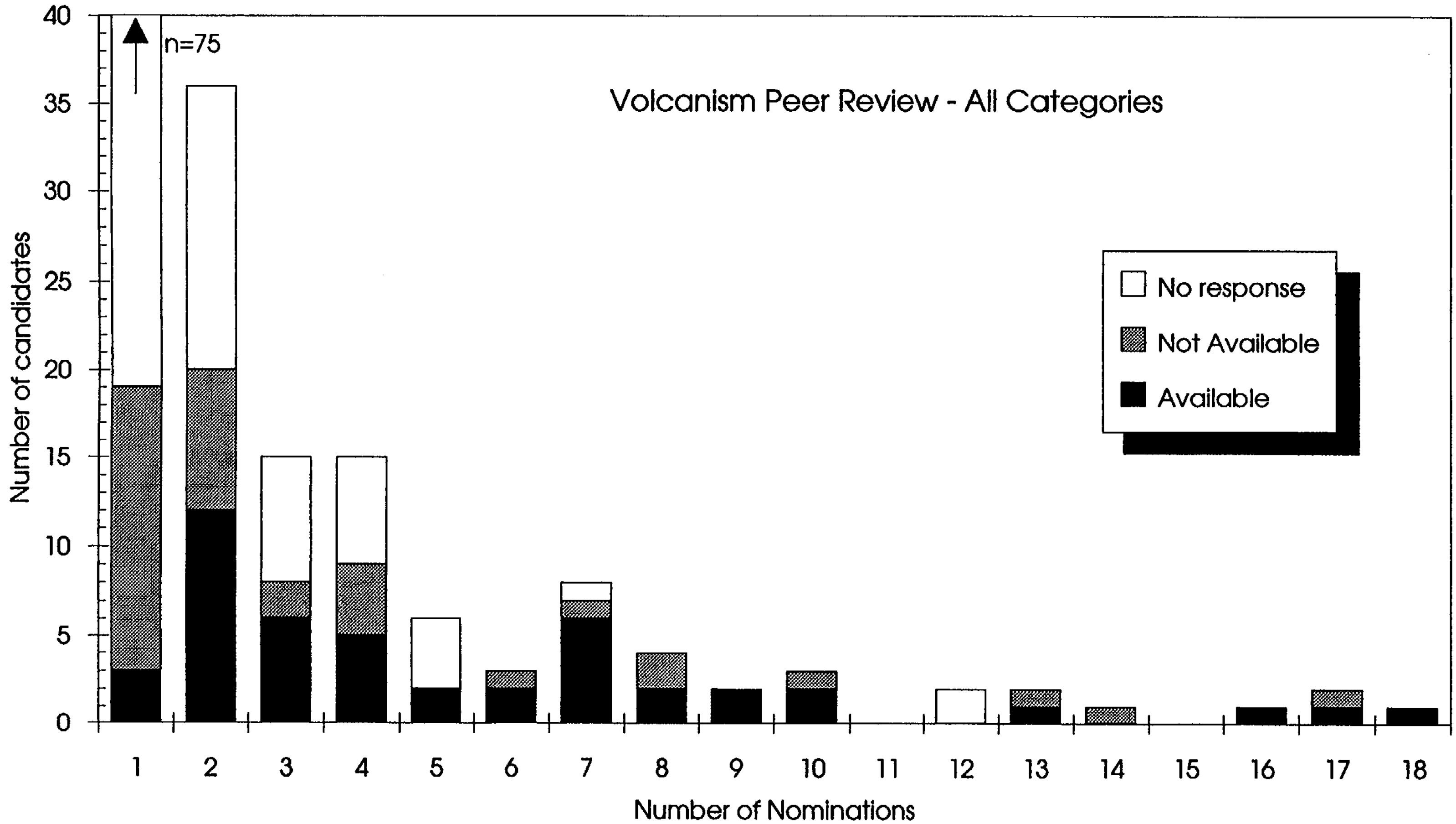

Figure 2-1. Compilation of nominations for individual expert-panel candidates. Candidates are grouped by the number of nominations they received and subdivided by availability if so indicated. The leading four available nominees are expert panel members. The fifth member had nine nominations but was selected based on the need for his speciality on the review panel. The two candidates with ten nominations lacked expertise in this speciality.

- Dr. Peter Lipman, USGS, Menlo Park, California. Dr. Lipman's research for the past 30 yr has focused on a wide range of topics, including the volcanic geology of the Basin and Range Province, physical volcanology, volcanic hazards, and the petrology of basaltic volcanic systems. He has published over 100 papers on these topics. In addition to being the Chief of the USGS Branch of Volcanic and Geothermal Processes, he is a Fellow of three professional societies and has received numerous scientific awards and honors. He has served as associate editor of three widely cited journals and has a distinguished record of service in professional societies.

- Dr. Alexander McBirney, University of Oregon (Emeritus), Eugene, Oregon. Dr. McBirney's research for the past 30 yr has focused on a wide range of topics, including physical volcanology, igneous petrology, volcanic hazards, and probability modeling. He was Editor-in Chief of the *Journal of Volcanology and Geothermal Research*, recipient of the prestigious N.L. Bowen award from the American Geophysical Union, and a Fellow of four professional societies. He also has served on numerous review committees for volcanic hazards evaluation and mitigation.

- Dr. Stephen Self, University of Hawaii, Honolulu, Hawaii. Dr. Self's research for the past 20 yr has focused on a wide range of topics, including physical volcanology, igneous petrology, and basaltic volcanic systems. In addition to being a Professor of Geology at the University of Hawaii since 1990, he has been on the editorial board for *Geology* and the *Journal of Volcanology and Geothermal Research*, and is a Fellow of the Geological Society of America. He also has served on numerous review committees and chaired society meetings on volcanic hazards evaluation and mitigation.

- Dr. George Walker, University of Hawaii, Honolulu, Hawaii. Dr. Walker's research for the past 35 yr has focused on a wide range of topics, including physical volcanology, igneous petrology, and basaltic volcanic systems. In addition to being the Gordon A. Macdonald Professor of Geology at the University of Hawaii since 1981, he is a Fellow of three professional societies and has received numerous scientific awards and honors. He also has served on numerous review committees and chaired society meetings on volcanic hazards evaluation and mitigation.

Drs. Delaney and Lipman could not be hired directly as consultants, as they are full-time employees of the Federal Government, the USGS. With the approval of their Branch Chief, Dr. Manuel Nathenson, the CNWRA was able to subcontract to the USGS for their services. Implementing this subcontract requires at least 6 weeks after the contractors have cleared conflict of interest review.

In preparation for the review, expert-panel members were sent a scope of work (Appendix D), the annotated outline for the review (Appendix C), and copies of the reports contained in the annotated outline. A total of 48 hr was allotted to the reviewers to review these documents and prepare for the meeting. The amount of time necessary for the reviewers to prepare for the meeting ranged from 8 to 48 hr.

The review meeting was held in San Antonio, Texas, on October 3–4, 1994. Staff from the CNWRA, NRC's Advisory Committe on Nuclear Waste (ACNW), NRC Division of Regulatory Research (NRC-RES) and NRC Division of Nuclear Materials Safety and Safeguards (NRC-NMSS), now the Division of Waste Management (NRC-DWM) also attended and participated in the meeting. The meeting agenda is given in Appendix E. After synopses on the CNWRA and its role in the Yucca Mountain repository program, panel members caucused and elected Dr. Peter Lipman as Chair for the meeting. The duties of the Chair were to keep discussions focused and to ensure that adequate time was allotted to discuss the main topics of the CNWRA volcanism research programs. Although the discussions were led by the review panel, the meeting generally followed the proposed agenda (Appendix E). The major points of discussion during the review are contained in the panel member's reports, which are presented in Section 3.

Following the San Antonio meeting, CNWRA and NRC staff and the panel members traveled to Crater Flat, Nevada, immediately southwest of the candidate repository site, to examine Quaternary and Pliocene volcanic features for 2 days. The group also examined faults and dikes in the Fortification Hill area, Arizona, for half a day. The purpose of this trip was to provide the reviewers with first-hand experience on these volcanoes and obtain insights into the processes represented by igneous activity in these areas. All the expert-panel members concluded that the field trip was a vital part of the review meeting that clarified many of the geological problems associated with YMR igneous activity. The major points of discussion on the field trip also are summarized in Section 3.

3 EXPERT-PANEL REVIEW RESULTS

After the expert-panel meeting, the panel members sent their final reports to the Chair, Dr. Peter Lipman. In addition to his individual report, Dr. Lipman also prepared a summary and overview of the individual reports (Appendix F). Individual panel-member reports are contained in Appendix G. Section 3 of this report provides a summary of each individual's report on CNWRA volcanism research, a synopsis of major recommendations and proposed program modifications, and summaries of individual observations of volcanic features observed on the field trip.

3.1 SUMMARY OF INDIVIDUAL REPORTS

Comments in this section are presented alphabetically by author. Each section begins with a direct quote of the reviewer that succinctly summarizes his overall opinion of the CNWRA volcanism programs. Annotated summaries of the author's comments are provided as bulleted items. The full text of the original comments by each expert-panel member is in Appendix G.

3.1.1 Comments by Dr. Paul Delaney

"The NRC is being well served by the CNWRA volcanism research group. The program is well planned, although overly bureaucratic in the sense that too many reports have been written to document a worthwhile but quite finite set of results. Yet, judging from those written materials provided to us and from the oral presentations and leadership of the field trip, Chuck Connor and Brittain Hill are informed and motivated workers, and certainly opinionated; they are fully capable of undertaking independent research and of judging results generated by others concerning volcanic hazards near Yucca Mountain."

- No direct modern analogs exist for Basin and Range (B&R) basaltic volcanism. Proposed analogs (i.e., Tolbachik, Cerro Negro, and Parícutin) may stretch the relationship, but the methodology is sound, as is the need for comparisons with active volcanic processes. Research needs to focus on processes, versus comparison with analog eruptions.
  - High-level magma reservoirs at Tolbachik may affect thermal models.
  - Analog studies with field work in other western United States basaltic fields should be continued.
- Subvolcanic structures, such as dike length, width, brecciation, and the occurrences of necks and plugs with depth, need to be compiled from the literature or through studies in appropriate western United States basaltic fields.
- Workers need to critically evaluate current distinctions between Pliocene-to-Recent activity, post-caldera activity, and basalt activity associated with silicic caldera eruptions in the YMR (e.g., Crowe et al., 1986); are these distinctions arbitrary?
- Additional work needs to be done on basaltic volcanoes in the YMR, if possible.
  - Physical volcanology studies (granulometry, xenoliths, alteration, analogy to active processes) are only preliminary in published work.

- A geographic information system (GIS) is not a useful research tool, instead it is more suited to data storage.

  — Current CNWRA-GIS efforts are appropriate.

  — Use when minimal effort or cost is required.

- More physical significance should be built in probability models. The nonhomogeneous approach is good (Connor and Hill, 1993), and the approach needs to be presented in the reviewed literature.

- The possibility that shallow basaltic dikes can create a pressure gradient to circulate groundwater upwards and cool the surrounding wall rock should be evaluated.

- Publications in refereed journals should be emphasized and the administrative load should be decreased.

3.1.2 Comments by Dr. Peter Lipman

"My over-riding impression is that CNWRA volcanism research is well planned and staffed by able young scientists who are highly enthusiastic about their work, are well-founded in modern volcanologic concepts, and should [be] able to provide critical expertise for review and independent evaluation of the volcanic-hazard issues that might impact nuclear waste-disposal plans at Yucca Mountain and elsewhere."

- Increase studies of YMR basaltic volcanism.

  — Examine Miocene and younger basaltic activity associated with calderas as a possibly distinct system from the Crater Flat area.

  — Augment physical volcanological studies, especially granulometry and xenolith studies.

  — Examine possible reasons for the apparent lack of preserved glass inclusions in olivines, which are relatively abundant in olivines in tholeiitic basalts.

  — Continue to evaluate resolution of geophysical methods and subsurface shallow structures.

  — Need to have a better understanding of the Miocene magmato-tectonic history of Walker Lane and Southwest Nevada Volcanic Field to evaluate Pliocene and younger YMR basaltic volcanism.

- Examine other relatively young B&R volcanoes that may have preserved tephra deposits, as analogs to older volcanoes at the YMR.

- Rigorously evaluate validity of comparisons with historically active analogs.

  — Analog studies are valuable and should continue.

— Possible differences in the geological setting between analog and YMR volcanoes:

  - Arc-volcanic vs. transtensional tectonic setting.
  - Repeated intrusions in shallow crust.
  - Differences in viscosity due to crystallinity or composition effects.
  - Depth to groundwater.

- Consider the 1973 eruption of Heimay, Iceland, as a potential analog for YMR basaltic volcanism.

- Reset priorities of VSBR to more urgent tasks.

  — CNWRA researchers may be doing too much.

- GIS compilation has great potential for comparisons between B&R areas but needs to focus on specific issues.

  — Questions on the sufficiency of data in GIS. Data needs include volumes, compositions, ages, subsurface structures, etc., which may not be available for most areas.

- Increase number of peer-reviewed publications and decrease "administrative" documents.

- Involve the tectonics and hydrology groups at CNWRA, Los Alamos National Laboratory (LANL), and USGS in volcanism research, when possible.

3.1.3 Comments by Dr. Alexander McBirney

"The combined meeting and field trips during the week of 3-7 October were exceptionally well organized and effective. They provided a clear picture of the project and the problems involved in the assessment of volcanic hazards. I was impressed with the thoroughness of the studies completed by the Center for Nuclear Waste Regulatory Analyses and concluded that their approach has been logical and efficient."

Dr. McBirney's comments focused on probability models, essentially confirming the Connor and Hill (1993) nonhomogeneous Poisson models.

- Probability models are limited by available YMR data. Need to:

  — Determine ages and compositions of Amargosa Valley aeromagnetic anomalies by drilling.

  — Discard older dates and obtain new age determinations using best available techniques at a single laboratory.

- Provide geologic basis for including or excluding vents from probability models.
  - Buckboard Mesa's association with the Miocene caldera structures may lessen its significance relative to Crater Flat volcanoes associated with regional structures.
- Evaluate tectonic data and incorporate it into probability models.
  - Quaternary volcanism is apparently controlled by E-W-trending dilation on right-lateral fault system, independent of the Miocene caldera system.
  - For near-neighbor calculations, an ellipse elongated parallel to fault trend appears more appropriate than a circle.
  - Springerville Volcanic Field is significantly different from the YMR, Snake River Plain, Iceland, or S. Guatemala, where cones are closely related to linear structural features.

3.1.4 Comments by Dr. Stephen Self

"I sincerely thank the scientists of the SwRI-CNWRA volcanism Research group...for an excellently organized, informative, and educational experience during the panel meeting. I am sure that I speak for all my fellow panel members in saying that we received all the information and help that we could have wished for. I felt that there were no gaps in the knowledge that it was appropriate for the CNWRA group to impart to us, that all sides of the issues involving young mafic volcanism in the Yucca Mountain region were fairly represented, and that our discussions were frank and open. NRC and CNWRA are fortunate to have such talented and dedicated young researchers pursuing the problems of recent volcanism in the vicinity of the proposed nuclear waste repository."

- Conduct more research on YMR basaltic volcanoes.
  - There is a lack of physical volcanological data for most YMR centers. These data need to be collected and modeled using research advances from the last decade.
  - Drill and evaluate the Amargosa Valley aeromagnetic anomalies.
  - Evaluate the proposed hypothesis of waning magmatism more closely, with respect to periodicity, explosivity, volume etc.
- Analog volcanoes need additional evaluation. These studies are, however, essential and provide needed comparisons to B&R data.
  - The analogs are good choices based on the available information, but unpublished data may indicate these eruptions were more explosive than represented in the YMR.
  - Cerro Negro and Parícutin likely have more viscous magmas due to microcrystallinity.
  - Parts of Tolbachik and 1973 Heimay may be better analogs.

- Slower cooling at Tolbachik may be artifact of larger volumes of subjacent magma in this eruption.

- Need to continue physical volcanological studies at analogs to understand processes.

- Tank experiments may be useful in evaluating magma interactions with repository. Modeled magma injected through a viscous medium with a void to see if intrusions stagnate or penetrate to the surface.

  - Consider that there might be a favorable side to magmatic intrusion.

- Dike-fault interaction studies are well founded and should be expanded.

  - Examine overall tectonic controls on mafic magmatism in YMR.

- Increase volcanological study of similar B&R systems to compare with new YMR data.

  - These data are not present in the literature.

  - Continue with geochemical and magma property compilations in the GIS. Obtain new data as needed.

- Reconsider the basis for the caldera and post-caldera basalt divisions. Consider that the "caldera-influenced" system may be distinct from Crater Flat system.

- Consider that future climate changes might be wetter, and re-evaluate the likelihood of magma-water interactions during future eruptions.

- Conduct more work on the sources of variation in locations of future events, limits to probability models, and incorporation of geological data.

- Reduce the number of internal reports to create more time for original research and publications.

3.1.5 Comments by Dr. George Walker

"The volcanism programs are well conceived, and the personnel are energetic and enthusiastic people who are well capable of implementing the programs. These personnel have available a great number of small volcanoes in the southern part of the Basin and Range Province, extending from Donner Pass/Truckee to southeast of Cima. If I were in their position, I would range widely over this province selecting suitable examples for detailed study."

- Decrease the amount of unnecessary paperwork and nonpublished reports. Increase the number of peer-reviewed publications.

- Conduct physical volcanological studies at analogous B&R volcanic fields.

- Granulometry of the deposits is the most important study to undertake.
- Granulometry studies have not been done at these volcanoes.
- Range widely over the western Great Basin (WGB) selecting suitable examples for detailed study.

- Analog work is sound and should continue.
  - Analogs may be more viscous than YMR due to higher microcrystallinity.
  - Continue emphasis on eruption dynamics.

- Anisotropy of magnetic susceptibility (AMS) can determine magma-flow directions in dikes and may be useful in dike-fault studies.

- Concern that silicic volcanism issues have not been explored sufficiently.
  - Evaluate the conditions that may reactivate silicic magmatism.

- Ancient (2,500-yr old) tunnels in ignimbrites in Italy may be long-term analogs for the Yucca Mountain (YM) tunnels.

3.2 SUMMARY OF CENTRAL THEMES AND PROPOSED ACTIONS

Actions recommended by CNWRA in this section for modifying volcanism research in response to the peer reviewers' comments require further discussion with and possible modification by the NRC staff before they are implemented in the volcanism research projects. The reviewer's comments are grouped into general recommendations and recommendations specific to each volcanism research project. For each comment, specific recommendations for implementation are provided.

3.2.1 General Improvements

- Present more of the research results in peer-reviewed literature.

  Action: CNWRA staff agree that publications in the reviewed literature are an important goal. Upcoming deliverables on probability modeling, eruption dynamics, and volcano degassing will be written for publication beyond delivery to the NRC. Although it is recognized that the technical support provided to the NRC often results in reports not publishable in reviewed journals, these reports still are valuable and necessary documents for the NRC.

- Increase scientific interactions with tectonics and hydrology groups at CNWRA, USGS, and LANL.

  Action: Research already involves collaboration with CNWRA tectonics, hydrology, and performance assessment groups. Because of conflict of interest issues and the need to independently review work by DOE and its contractors, collaborative research is not possible with DOE organizations such as LANL. Interactions with other groups occur at scientific meetings and through informal communications. There are, however, programmatic limitations on the amount of collaborative research possible.

- Current research programs are somewhat ambitious, and they may need to be refocused in order to accomplish priority research within the time available.

Action: This comment is especially relevant in view of the DOE Proposed Program Approach (PPA), which plans for a high-level finding in volcanism sometime in mid-1997. CNWRA staff will meet with NRC RES and DWM staff early in 1995 to evaluate volcanism research strategies. Discussions will focus on determining research tasks that are the most critical to evaluating the proposed high-level finding. This immediate need must be balanced with the long-term support necessary to evaluate the DOE license application and to provide anticipated levels of technical assistance.

- Organize an invitational field workshop on the physical volcanology of the Crater Flat area volcanoes, including researchers not involved in YMR controversies.

Action: Sponsoring a workshop on physical volcanology is concomitant upon having physical volcanological data to discuss. One of the main recommendations of the expert-panel reviewers is for CNWRA researchers to collect these data for some YMR volcanoes. Such a workshop also is dependent on other researchers presenting actual data to support their hypotheses, rather than simply stating conclusions. Recommended CNWRA field work should be possible during 1995. The earliest feasible date for a physical volcanology workshop is thus late in 1995.

3.2.2 Recommendations Specific to the Volcanic Systems of the Basin and Range Project

- Conduct physical volcanological studies at YMR volcanoes.

Action: Physical volcanological studies should be conducted first at the Quaternary volcanoes of Crater Flat and Lathrop Wells, expanding to the Pliocene volcanoes of that area. These studies are necessary to confirm DOE eruption dynamics models and to insure that appropriate data are available to accurately compare analog and YMR volcanoes. These studies will involve:

— Granulometry of fall deposits both proximal and, if possible, distal to the main vents.

— Characterization of the physical properties of clasts in cone and fall deposits including crystallinity, vesicularity, density, and deformation.

— Xenolith composition, abundance, and morphology including determining the degree of magma-xenolith interaction.

Propose these studies be conducted during the first half of 1995, weather permitting.

- Conduct physical volcanological studies at suitable B&R volcanoes, because these data are not available from the literature.

  Action: The same types of physical volcanological studies proposed for YMR volcanoes will be conducted at suitable B&R volcanoes. Relatively young volcanoes of the Cima, Coso, Big Pine, and Lunar Crater volcanic fields will be evaluated for suitability and appropriate studies conducted during 1995.

- Investigate possible spatial and temporal divisions in YMR periods of basaltic activity. Consider that present divisions (younger and older post-caldera) may be artificial. Neogene and younger basalts associated with the caldera system also may represent a system distinct from Neogene and younger basalts in the Crater Flat area and south.

  Action: Continue evaluation of available data for Neogene and younger basalts of the YMR and adjacent areas. Obtain sample locations and complete data for analyses contained in DOE studies. Continue petrological study of YMR basalts to evaluate these hypotheses. Expand CNWRA petrology studies to include Pliocene basalts of the Greenwater Range/Funeral Formation, which may be contemporaneous and petrogenetically related to basalts in Amargosa Valley and Crater Flat.

- Continue characterization of volcanic and subvolcanic features for appropriate B&R volcanic systems.

  Action: This is an ongoing task in the Volcanism GIS work and will continue through 1995.

- Minimize efforts in developing the Volcanism GIS.

  Action: Although some criticisms were leveled at GIS in general, reviewers felt that the current level of work in the Volcanism GIS was appropriate. Other reviewer's comments in this section clearly indicate that the Volcanism GIS is a useful research tool as well as a valuable data custodian for the license review processes. Planned work in the Volcanism GIS will continue at current levels. Ongoing work includes correlation of dated lava flows with appropriate vents and the incorporation of geophysical data into YMR and San Francisco Volcanic Field coverages.

- Continue work in developing nonhomogeneous probability models. Incorporate the apparent effects of tectonic control into these models, possibly by using ellipses in the near-neighbor calculations. Publish these models in the reviewed literature.

Action: These are ongoing FY95 tasks in the VSBR research project, including the incorporation of structural or other geological data into these probability models. Revisions are being made to a *Journal of Geophysical Research* manuscript on the nonhomogeneous probability models.

- Determine nature of the Amargosa Valley anomalies through direct drilling.

  Action: Evaluate if these anomalies will be drilled by the DOE in a timely fashion relative to their PPA. If no drilling is planned, indicate to the NRC that the CNWRA considers the study of these anomalies critical to review of DOE volcanism research.

- Redate basalts of the YMR using a single method and laboratory so as to eliminate the large apparent uncertainties currently present in these data.

  Action: Continue to evaluate the precision and accuracy of new age estimates for YMR basalts as they become available from LANL, USGS, and other groups. Encourage discussions on the precision and accuracy of the newer data and evaluate if the newer data truly are an improvement over older published data. Request that the DOE provide data to substantiate that published and unpublished age estimates truly represent igneous events and have not been affected by open-system processes.

- Re-examine the possible occurrence of renewed silicic magmatism in the YMR.

  Action: Not currently an active research topic, but the possibility of renewed silicic magmatism in the YMR has not been examined in detail. Need to evaluate the geologic conditions that lead to the formation of a small, isolated 1-Ma rhyolite dome in the Big Pine Volcanic Field, California, as possible analog for renewed YMR silicic magmatism.

3.2.3 Recommendations Specific to the Field Volcanism Project

- Eruptions at modern analog volcanoes (Tolbachik, Cerro Negro, and Parícutin) need to be evaluated for rheological differences with YMR volcanoes.

  Action: Data in the published literature show these volcanoes are comparable with the YMR volcanoes (Connor, 1993). However, the reviewers believed that unpublished data, especially on the microcrystallinity of the erupting magmas, may show that the analog volcano eruptions were more explosive than YMR volcanic eruptions. Petrologic studies at YMR and analog volcanoes are designed to constrain the extensive and intensive variables that control eruption explosivity in these magmatic systems. These variables are composition (including magmatic water content), temperature, crystallinity, vesicularity, and magma ascent and eruption rates. As work continues on the analog volcanoes, these data will be used to evaluate similarities and differences between the analog and YMR volcanoes.

Research subsequent to the review shows that scoria from the 1975 Tolbachik eruption have similar to lower microcrystallinities than scoria from studied Quaternary YMR volcanoes (Hill and Connor, 1995). This initial research supports the compositional, petrographic, and geologic data presented in Connor (1993) that demonstrates the relatively high degree of analogy between these volcanic systems. Rigorous evaluation of this analogy will continue as research progresses and similar studies will be conducted as planned at YMR and other analog volcanoes.

- Other potential differences between the geologic setting of modern analog and YMR volcanoes need to be rigorously evaluated:

  — Arc-volcanic versus transtensional tectonic setting.

  — Presence of possible upper-crustal magma reservoirs.

  — Role of possible shallow groundwater on eruptions.

  Action: Arc volcanoes represent the best possible modern analogs with YMR basaltic volcanism, although obvious differences exist between these geological settings. Similar differences exist between the YMR and volcanic fields on the Colorado Plateau or in Hawaii. Ongoing but undocumented work at Tolbachik Volcano has addressed the significance of some of these differences. For example, temperature measurements at the cooling cinder cones and dikes are not affected by regional heat flow or local thermal anomalies induced by upper-crustal magma reservoirs. The depth to the water table at Tolbachik is about 500 m, which is the same depth as at Yucca Mountain. Work at any analog to the YMR, either historical or ancient, must document how potentially important differences in the geologic setting may affect the processes under investigation. This work is an ongoing part of CNWRA volcanism analog studies.

- Volcanic analog studies should consider the 1973 eruption of Heimay, Iceland, which may represent more typical Strombolian eruption processes than present analogs.

  Action: Data on this eruption will be compiled from the available literature for use in CNWRA volcanism analog studies. Critical data, such as the microcrystallinity of the magma or pre-eruption volatile contents, may need to be obtained. These data likely can be acquired from samples provided by researchers studying this volcano.

- Continue characterization of subvolcanic structures for appropriate B&R systems. Consider expanding work on subvolcanic structures to include AMS studies, which can determine magma flow directions.

  Action: The physical dimensions of subvolcanic structures, such as dikes, necks, and plugs, are entered into coverages in the Volcanism GIS when such data are available. There are few directed studies of these features for volcanic systems in the WGB, and geological mapping of these fields is usually at too coarse a scale to accurately measure these features from maps. However, work will continue to compile this information where available. In addition, ongoing field research in the Reveille Range, Nevada, by E.I. Smith and coworkers at the University of Nevada, Las Vegas, likely will provide a large amount of information on these structures for a geological environment very similar to the YMR.

AMS studies of magma flow directions in dikes are potentially useful for fault-dike interaction models. This research task is ongoing with the Tectonics research programs. As these studies progress, the possibility of involving additional researchers with AMS experience will be explored.

- Viscous-fluid experiments simulating the injection of magma into the repository may provide useful constraints on potential magma-repository interactions.

  Action: One of the potentially most difficult problems to address during licensing will be the effects of basaltic magma upon repository performance. There are no naturally occurring analogs for ascending basaltic magma encountering a repository-sized void at 300-m depths. Evaluating these effects will involve a combination of modeling the decompression and fragmentation of rapidly depressurized magma and data from near-surface subvolcanic processes. Unquestionably, tank experiments scaled to simulate magma-repository interactions would provide useful information. These experiments are, however, well beyond the scope of the current CNWRA volcanism research programs. As additional CNWRA research programs are developed, the possibility of conducting tank experiments with outside consultants will be explored. The DOE also should consider conducting such experiments to support ongoing magma-repository interaction studies.

- Consider that future climates may be wetter and increase the possibility for magma-water interactions during eruptions.

  Action: Crowe et al. (1986) evaluated the potential for hydromagmatic eruptions at the candidate YMR repository using current hydrologic and climatic conditions. However, a large amount of research on future climatic and hydrologic conditions has been conducted since that time. The results of this research need to be applied to the problem of possible future hydromagmatic eruptions in the YMR. In addition, the importance of fracture-dominated flow in the Yucca Mountain system needs to be evaluated with regard to hydromagmatic eruption potential. Future work on eruption dynamics in the Field Volcanism Research Project will investigate this potential further.

- Evaluate possibility that cooling dikes can create a negative pressure gradient in the saturated zone and induce upward water flow and low-temperature hydrothermal alteration within the dike.

  Action: Dikes at Fortification Hill, Arizona, and elsewhere commonly contain zeolite and carbonate alteration minerals whereas the surrounding wall rock is relatively fresh. A cooling, permeable dike below the water table may create a negative pressure gradient in the saturated zone and induce upward water flow. This influx of water into the dike may control the development of alteration minerals within the dike and inhibit alteration of the wall rock. Current studies will be expanded to accurately characterize the alteration mineralogy of the Fortification Hill dikes. These data can then be used to evaluate the proposed cooling model.

3.3 COMMENTS RESULTING FROM THE FIELD TRIP

Although the CNWRA peer-review was not designed to evaluate scientific problems at the YMR, a field trip was provided to acquaint the expert-panel members with the volcanic geology of the area. All the review-panel members found the trip extremely valuable for their understanding of the CNWRA research problems. The reviewers made a number of field observations on the Lathrop Wells and Crater Flat volcanoes, which are by their own admission preliminary in nature. However, these observations illustrate the types of controversies independent scientists perceive based on published reports and direct observations. These observations also serve as a guide for the types of field-based research CNWRA staff can conduct to evaluate these problems, which undoubtedly will remain during prelicensing reviews and interactions. The detailed comments are contained in Appendix G and are summarized in this section by volcano.

Lathrop Wells

- Reported surge deposits (Crowe et al., 1986; 1988) on the proximal northwestern sector from the cone may represent eolian rather than hydromagmatic processes. Evidence supporting this interpretation includes: (i) the lateral discontinuity of the beds suggests dune bedding, (ii) a large proportion of the clasts are silicic volcanic and not basaltic, (iii) the bedding dip is consistently steeper than the paleosurface, and (iv) the clasts are relatively fine grained.

- Scoria mounds on the proximal eastern sector from the cone probably do not represent small vents as reported (Crowe et al., 1988). Evidence against these mounds being vents includes: (i) lack of central craters or agglutinate, (ii) occurrence on successive flow lobes, (iii) alignments are arcuate along broad lava-flow surfaces, (iv) mounds occur near distal flow margins. More likely explanations for the origin of these mounds include: (i) pieces of the cone rafted by lava flows during earlier stages of the eruption, which is a common occurrence in observed eruptions; and (ii) accumulations of proximal scoria-fall subsequently disrupted by movement on active lava flows.

- Shallow crustal xenoliths are reported as predominately from the Tiva Canyon Tuff (Crowe et al., 1983). Most xenoliths observed on the trip were from a crystal-lithic tuffaceous wacke and a crystal-rich, poorly welded ignimbrite (Rainier Mesa Tuff?). Sparse xenoliths of crystal-poor densely welded ignimbrite may represent either Tiva Canyon or Topopah Spring Tuffs.

- The main cone is highly modified by erosive processes, even though it lacks rilling and channeling on the outer flanks. Erosional modification is indicated by: (i) inner crater walls reside at angles much less than repose; (ii) structure common on the rims of youthful cones are absent; and (iii) cone slope deposits are permeated by windblown sand, which may have impeded rill erosion.

Little Cone SW

- Deposits appear very similar to Lathrop Wells, with abundant evidence of downslope transport of clasts by grainflow. Deposits are more bedded than Lathrop Wells, possibly indicating a more pulsed eruption. Clasts appear to have a more uniform degree of vesicularity and are somewhat less vesicular than Lathrop Wells.

- Scoria-fall deposits likely are preserved on the surrounding lava flows and should be examined if possible.

Red Cone

- Clasts on the south side of the cone have very low vesicularity and may represent Vulcanian-type eruptions of near-solidus ejecta during late stages of cone growth. Bedding is noticeably absent in these deposits.

- Most of the dikes mapped on lava flows (Smith et al., 1990) are more plausibly explained as ramp structures or pressure ridges. These features are arcuate and follow flow lobe patterns, and occasionally have ropey outer surfaces.

4 CONCLUSIONS

The expert-panel review of the CNWRA volcanism research programs met all its objectives successfully. Five independent experts in volcanology examined the research programs in detail. The reviewers concluded that the CNWRA research programs are being conducted by well-qualified personnel. CNWRA volcanism research programs are organized and conducted using sound scientific methods and results from these programs are scientifically defendable. In addition, the CNWRA research addresses relevant and important geological problems at the YMR.

The major overall recommendations for improvement to the CNWRA volcanism research programs are to:

- Increase studies of basaltic volcanism in the YMR, including Miocene basaltic activity associated with waning stages of caldera magmatism.
- Conduct independent physical volcanological studies of Quaternary YMR basaltic volcanoes. Supplement these studies with data from other appropriate B&R and modern analog volcanoes.
- Continue to evaluate the relationships between YMR and modern analog volcanoes as data from planned studies become available.
- Prioritize project goals to focus on the most urgent tasks.
- Allocate more time for detailed studies that result in peer-reviewed journal publications.

None of these recommendations represent major changes to the CNWRA volcanism research programs, although their implementation will certainly improve the quality of support provided to the NRC by the CNWRA.

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APPENDIX A

NOMINATION ELICITATION LETTER

Center for Nuclear Waste Regulatory Analyses

6220 CULEBRA ROAD • P.O. DRAWER 28510 • SAN ANTONIO, TEXAS, U.S.A. 78228-0510
(210) 522-5160 • FAX (210) 522-5155

Contract No. NRC-20-93-005
Account No. 20-5704-123

Address

Dear :

The Center for Nuclear Waste Regulatory Analyses (CNWRA) is a federally funded research and development center that supports the Nuclear Regulatory Commission High-Level Nuclear Waste Repository Licensing Program. A candidate repository site at Yucca Mountain, Nevada, is currently under evaluation. Basaltic volcanism has been a characteristic of the Yucca Mountain Region (YMR) since about 8 Ma, with six Quaternary eruptions occurring within about 20 km of the candidate repository site. As part of this NRC support, the CNWRA has undertaken a volcanism research program to assess the probability and likely consequences of basaltic magmatism that may occur in the YMR during the next 10,000 yr.

The CNWRA volcanism Research program has been fully functional for only about a year. I am organizing an independent review of this program in order to evaluate the initial research results and further refine proposed research strategies and goals; the current research program is scheduled to continue into 1997. The first step in this review is to select a panel of experts in the field of basaltic volcanism. Because you're well known in the relevant fields of volcanology, I need your assistance in identifying candidates for the five-member review panel.

We are seeking recognized experts in the fields of basaltic eruption dynamics, heat and mass-transfer processes at basaltic volcanoes, probability modeling for volcanic fields, and the Pliocene-to-Quaternary volcanology of the western Basin and Range Province of North America. The general goals of this review are to (i) examine the overall objectives and approaches of CNWRA volcanism research; (ii) improve and possibly expand the research scope and methodologies; and (iii) evaluate interpretations of the available data and explore alternative hypotheses. Reviewers are expected to focus and lead discussions on issues that they deem important, rather than be restricted to a predetermined agenda. I anticipate holding a 2-day review meeting in San Antonio, Texas and possibly a 2-day field trip to the Yucca Mountain area during September 1994; individual review recommendations will need to be submitted by November 21, 1994. The selected experts will be contracted by the CNWRA as consultants and will be paid for their time and associated expenses; I anticipate a total time commitment of about 140 hours, of which about 60 hours will be for the meeting, field trip, and travel.

Washington Office • Crystal Gateway One, Suite 1102 • 1235 Jefferson Davis Hwy. • Arlington, Virginia, 22202-3293

I would like to know if you would be interested in participating in this peer-review panel. If so, or if you would like more information on this review, please contact me directly at your earliest convenience. In any event, I would greatly appreciate the names of 8-10 people that you would regard as experts in the above fields of volcanology. I will, of course, keep these names confidential, and am only using this information to compile a list of potential candidates for the panel. After this general solicitation is complete, I will then contact the potential panel members directly to further explore their interest and availability. Due to possible conflicts-of-interest, we unfortunately are unable to have employees of the U.S. Department of Energy and associated national laboratories (e.g., Los Alamos, Sandia, Lawrence Livermore) on this review panel. We need to finalize the panel membership before the middle of June 1994, and thus hope that you are able to respond to this request within the next couple of weeks.

Yours truly,

Dr. Brittain E. Hill

APPENDIX B

FORMAL LETTER OF INVITATION FOR PEER-REVIEW PANEL

Center for Nuclear Waste Regulatory Analyses

6220 CULEBRA ROAD • P.O. DRAWER 28510 • SAN ANTONIO, TEXAS, U.S.A. 78228-0510
(210) 522-5160 • FAX (210) 522-5155

Contract No. NRC-20-93-005
Account No. 20-5704-123

Address

Dear :

Recently Dr. Brittain Hill of the Center for Nuclear Waste Regulatory Analyses (CNWRA) contacted you about participating on a peer-review panel for volcanism research at the CNWRA. Having received your preliminary indication of interest, we are initiating formalities to acquire your services as a consultant to the CNWRA for this purpose. A brief introduction to the CNWRA and an outline of the review we desire is included in this letter, along with a request for information from you to permit us to initiate a contract.

The CNWRA is a Federally Funded Research and Development Center that has been established with a mission to provide quality research and technical assistance to the U.S. Nuclear Regulatory Commission (NRC) toward licensing the first national high-level nuclear waste (HLW) repository. The CNWRA is situated at the Southwest Research Institute (SwRI) in San Antonio, Texas, and is operated by SwRI. The CNWRA currently has professional staff spanning all areas to geosciences and engineering relevant to HLW geologic repositories.

As the licensing authority, the NRC has a strong interest in the volcanic geology of the potential HLW repository environment at Yucca Mountain, Nevada, and sponsors several research projects at the CNWRA to investigate this issue. Basaltic volcanism has been a characteristic of the Yucca Mountain Region (YMR) since about 8 Ma, with six Quaternary eruptions occurring within about 20 km of the candidate repository site. The present performance standard for the HLW repository requires that no significant release of HLW to the accessible environment occurs during the next 10,000 years. Our current understanding of the YMR geologic system is that volcanic disruption is a low probability ($\leq 10^{-3}$ in 10,000 years) but high consequence event for HLW isolation. Volcanism research at the CNWRA is designed to assess the probability of volcanic disruption of the proposed repository and to evaluate the potential consequences of igneous activity on repository performance. This research is summarized in the enclosed outline.

Both the NRC and CNWRA recognize that peer-review will improve ongoing research programs significantly. The intended goals of the current review are to (i) examine the overall objectives and approaches of CNWRA volcanism research; (ii) improve and possibly expand the research scope and methodologies; and (iii) evaluate CNWRA's interpretations of the available data and hypotheses. The review panel will consist of five senior scientists such as yourself, with expertise in Basin and Range volcanism, basaltic eruption dynamics, volcanic heat and mass transfer processes, probability modeling, and basalt petrology. The CNWRA has developed and implemented a formal quality assurance program, which includes procedures for the performance of peer reviews. A copy of this procedure, CNWRA Quality Assurance Procedure QAP-002, is enclosed for your information.

Washington Office • Crystal Gateway One, Suite 1102 • 1235 Jefferson Davis Hwy. • Arlington, Virginia, 22202-3293

We anticipate holding the first part of the review at the CNWRA in San Antonio, Texas, beginning on Monday, October 3, 1994. The principal investigators on the CNWRA volcanism programs, Chuck Connor and Brittain Hill, will present a synopsis of CNWRA research activities. These presentations will supplement the study plans and reports which will be sent for you to review in mid-August. The expert-panel members will elect a chairman, who will preside over the meeting. The chairman will then lead discussions on the research program in general, followed by specific topics from the panel member's areas of expertise. Following two days of meeting in San Antonio, we will fly to Las Vegas on October 5 and travel to Beatty, Nevada. We will spend Thursday and Friday examining the Quaternary and Pliocene volcanoes of the Crater Flat area, Nevada, which is located adjacent to the candidate HLW repository site at Yucca Mountain. The field trip will help put the CNWRA research program and the Yucca Mountain region into the proper geologic context, and we also hope to benefit from your research experience in basaltic volcanism. The field trip will end in Las Vegas, Nevada, on Friday October 7, 1994.

We expect that the review of the background material and preparation for the panel meeting will require about 48 hours of your time. Participation in the meeting, field trip, and associated travel will require an additional 48 hours. Following the meeting, panel members are expected to produce a written report of about 10 pages, which provides their evaluation of the CNWRA research program and recommendations for improvement. We expect that the preparation of this report will require about 40 hours of your time, and that the report will be completed by the end of October, 1994.

To meet CNWRA Conflict of Interest requirements, and to assist us in setting up a consulting agreement, we must receive from you the following items:

- Conflict of Interest Statement (form and a sample copy of a letter enclosed)
- A copy of your current curriculum vitae
- Your fee schedule

We would appreciate your attention and quick response in supplying these items. Please send them to CNWRA, attention Anna Lopez. On execution of the consulting agreement, we will send you the following background materials to review: vitae for Drs. Connor and Hill, research project plans, CNWRA reports, journal articles, and abstracts related to these projects.

We greatly appreciate your interest in helping the NRC and the CNWRA in this matter of national importance. Drs. Connor and Hill will be conducting research at the Tolbachik volcanoes in Kamchatka, Russia, until August 8, 1994. If you have any questions about the review during that time, please contact Dr. David Ferrill (210-522-6082) or Dr. Larry McKague (210-522-5183) at the CNWRA.

Sincerely,

Dr. Budhi Sagar
Technical Director

Enclosures

cc: W. Patrick
CNWRA Directors
CNWRA Element Managers
B. Hill
C. Connor
D. Ferrill
A. Lopez

APPENDIX C

OUTLINE FOR THE EXPERT-PANEL REVIEW OF VOLCANISM RESEARCH AT THE CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

MAIN GOALS

- A critical review of the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain high-level waste (HLW) repository site
- Recommendation to improve research scope and methodologies, and investigate new issues that may not be part of the original research plans
- Evaluate interpretations of the available data, and explore alternative hypotheses

BASIC ISSUES IN CNWRA VOLCANISM RESEARCH

I. Synopsis of the Regulatory Basis for Doing Volcanism Research:

10 CFR 60.1: Nuclear Waste Policy Act (1982) and amendments task the DOE to receive and store high-level nuclear waste in a geologic repository.

10 CFR 60.3: DOE is required to obtain a license for the repository from the NRC.

40 CFR 191 Appendix B. A 10,000 year waste-isolation period is required, such that processes that have a greater than 1 in 10,000 probability of occurrence will not cause a significant health risk. The upper limit of that risk is generally defined by less than 1,000 health effects over 10,000 years per 100,000 tons of heavy metal of reactor fuel.

10 CFR 60.122: Siting criteria: The DOE must evaluate the repository site to demonstrate that the geologic setting and engineered barrier systems are sufficient to provide reasonable assurance that the performance objectives related to waste isolation will be met. For potentially adverse conditions (PAC), specific criteria must be met:

i) The PAC has been adequately investigated, including the extent the condition may be present but undetected; and
ii) The effect of the PAC on the site has been adequately evaluated using analyses which are sensitive to the PAC and assumptions which are not likely to underestimate its effect; and
iii) The PAC is shown
   a) to not affect significantly the ability of the repository to meet the performance objective related to waste isolation, or
   b) to be compensated by the presence of favorable conditions, or
   c) can be remedied

10 CFR 60.122c(15): Evidence of igneous activity since the start of the Quaternary Period, in the geologic setting of the repository, is a PAC.

10 CFR 60.122c(3): Potential for natural phenomena, such as volcanic activity, of such magnitude that large-scale surface impoundments could be created that could change the regional groundwater flow system, is also a PAC.

In essence, the NRC will have 3 years to evaluate the DOE license application, and determine if the proposed site could result in significant health risks to the population. This evaluation process is expected to be highly contentious and subject to intense scrutiny by numerous groups with extremely divergent views on nuclear waste in general and the proposed repository site at Yucca Mountain in particular. Early peer review of the CNWRA volcanism Research program is thus prudent and will enhance the overall quality of the program.

CNWRA volcanism Research developed around 8 basic Key Technical Uncertainties:

Key Technical Uncertainties (KTUs) were developed by the NRC to guide the research needed to effectively evaluate the DOE license application. For Igneous Activity, 3 specific and 5 general KTUs exist:

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

IV Developing a conceptual groundwater flow model
V Prediction of future changes in the hydrologic system (due to tectonism)
VI Conceptual model representation of the natural and engineered systems
VII Variability in the model parametric values
VIII Prediction of future system states (disruptive scenarios)

KTU Translation to basic research problems:

- Can't directly sample the current igneous system; too deep, processes operate >> years
- Can't directly observe what happened in past, must infer from geologic data
- Geologic processes in small-volume, continental basaltic volcanic systems have many uncertainties and these systems have not been examined in detail.
- Must extrapolate from current, undetermined state to 10,000 years into the future.
- There are large uncertainties in both the data and in the models that are difficult to constrain

This all distills down to that we must understand the 10,000 year probability and possible consequences of igneous activity on repository performance, and determine if the DOE has adequately investigated these issues in the License Application.

II. General CNWRA volcanism Research Project Objectives:

A. **Volcanic Systems of the Basin & Range Research Project**
   1. Relationship of Yucca Mountain to other B&R volcanic & structural areas
   2. GIS of western Great Basin (WGB) volcanic fields & structure
   3. Assessment of dating methods & uncertainty
   4. Assessment of uncertainty associated with available data on WGB
   5. Probability model development & testing
   6. Conceptual magmo-tectonic modeling & uncertainties

B. **Field Volcanism Research Project**
   1. Identification of historically active analog volcanoes for YMR
   2. Eruption dynamics from analogs and older deposits
   3. Thermal & degassing effects at active & preserved volcanoes
   4. Geophysical studies for resolution of subvolcanic features

III. Research Program Results and Products to date:

A. Major Milestones:
   1. Spatially nonhomogeneous Poisson probability models for the YMR
   2. Literature review of Basin & Range volcanism and tectonism, which concludes that the YMR is in the western Great Basin (WGB) magmo-tectonic subprovince
   3. Compilation of available data into a Geographic Information System for the Cima, Big Pine, Coso, and Reveille/Pancake Range volcanic fields. Ongoing work on Death Valley, Yucca Mountain, Pisgah-Amboy-Dish Hill, and others TBD
   4. Technical and regulatory basis for the study of recently active cinder cones, including White Paper synopsis
   5. Review and assessment of dating techniques for Quaternary and Neogene volcanic rocks
   6. Review of geophysical techniques applicable to basaltic volcanism issues
   7. Strategy to assess uncertainties in geologic models and data

B. Other written topics (Semi-annuals/abstracts/reports):
   1. Fault-dike interactions, including Fortification Hill, Nevada, field work
   2. Petrology of the YMR basalts especially volatile content determinations
   3. Heat and mass-transfer processes at small-volume basaltic systems
   4. Development of volcano cluster and alignment determination methodologies
   5. Initial cinder cone eruption energetics modeling

C. Ongoing and nonreported research:
   1. Degassing and soil-gas studies at Cerro Negro, Paricutin, and Tolbachik volcanoes
   2. Granulometry studies at Cerro Negro, Paricutin, and Tolbachik volcanoes
   3. Quantitative petrographic analyses
   4. Petrology of the YMR basaltic volcanoes

IV. What is required from reviewers:

A. Background material: In addition, ongoing CNWRA research needs to be summarized and included in the literature package.

1. Detailed review:
   a. Volcanic Systems of the Basin and Range Project Plan. 20 p.
   b. Field Volcanism Project Plan. 20 p.
   c. Technical Basis for the study of recently active cinder cones (Connor, 1993) IM 20-5704-141-001. 30 p.
   d. CNWRA Perspective on: Identification and use of modern analogs to Basin and Range Volcanism (1994). 5 p.

2. Review:
   a. Semi-Annual Research Reports for projects (summary reports): 1/92 (15 p.), 2/92 (26 p.), 1/93 (2 ch, 30 p.); 2/93 (2 ch, 40 p.); 1/94 (2 ch, 40 p.).
   b. Estimating the probability of volcanic disruption... Connor and Hill 1994, Focus '93 paper
   c. Uncertainty analysis strategy Connor and Hill, 1994.

3. Skim for familiarization:
   a. Review of Pertinent Literature on Volcanic-magmatic and tectonic history of the Basin and Range. CNWRA 92-025, 55 p.
   b. Review and Analysis of Dating Techniques for Neogene and Quaternary volcanic rocks. CNWRA 93-018, 80 p.
   c. The CNWRA volcanism Geographic Information System Database. CNWRA 94-004, 40 p.
   d. Review of Geophysical techniques. CNWRA 94-015. 80 p.
   e. Vaniman et al., 1982; Crowe et al., 1982, 1983; Crowe and Perry 1992; Valentine et al., 1993.
   f. Abstracts and Connor papers related to these topics (about 20 p.)

B. Detailed Review of Project Scope: Discussions will led by panel members and will focus on the main goals:

1. Critically review the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain HLW repository site

2. Recommendations to improve the research scope and methodologies, and investigate new issues that may not be part of the original research plans

3. Evaluate interpretations of the available data, and explore alternative hypotheses

C. Detailed Review of Specialty Areas: Essentially a peer review of written products in each expert's specialty area, and suggestions for improvement in specific areas.

D. Preparatory material on YMR geology for the field trip to Crater Flat. Reviewers include an evaluation of how the YMR fits into their experience, and what they see as the major research issues to be addressed for this area.

Reviews will consist of discussions in San Antonio and Crater Flat, Nevada, and a short (about 10 pages) independent written report from each panel member.

V. Schedule & plan for peer review:

FY94

1) Develop the objectives of the review in detail. Solicit input from NRC and CNWRA staff, and possible informal discussions with experts who are ineligible for the Review Panel.

2) Recruit the experts. Solicitations from 150 people, including NRC, USGS, domestic and international academic institutions, appropriate professional societies, journal editors. Formal selection for 5 individuals, with expertise in: B&R volcanism, Basaltic eruption modeling, Volcanic degassing/hydrothermal processes, Probability modeling.

3) Prepare documentation and information for expert review. Determine format and detailed instructions to reviewers for initial review, mid-August 1994.

4) Provide initial information and instructions to reviewers. Allow for about 6 days (48h) billable for initial overview and preparation.

5) Meet in San Antonio for overview and Connor-Hill presentations and discussions, October 3-4, 1994. Three days (24h) including travel time.

6) Field trip to Lathrop Wells and Quaternary-Pliocene Crater Flat volcanoes, October 5-7, 1994. Examine volcanism problems and controversies (polycyclic, ages, petrogenesis, eruption mechanisms, secondary effects) in the field. Return home with additional information and task for detailed review. Three days (24h) billable time including travel.

FY95

7) Reviewers prepare detailed report, addressing major goals of review, by October 28, 1994. Arrive at individual recommendations for improvement and validations of research approaches. Allow about 5 days (40h) billable.

8) Synthesize the 5 individual reports into Major Milestone for NRC-RES. Delivery date at end of February, 1995. Modify project plans or research strategies as appropriate.

APPENDIX D

SCOPE OF WORK FOR CNWRA VOLCANISM EXPERT-PANEL REVIEW

The work will be encompassed in one primary Task with four Subtasks, as follows:

The primary Task is to provide an expert review of the CNWRA volcanism research projects *Volcanic Systems of the Basin and Range* and *Field Volcanism*. The objectives of the review are to:

- Critically review the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain HLW repository site
- Provide recommendations to improve the research scope and methodologies, and investigate new issues that may not be part of the original research plans
- Evaluate interpretations of the available data, and explore alternative hypotheses

The expert-panel review will be accomplished by the following four Subtasks:

1) Review the literature produced under the CNWRA volcanism research projects, to become familiar with programmatic and technical goals. Detailed reviews will be conducted on study plans and critical reports (about 100 pages). Semi-annual reports and principal milestones (about 200 pages) will be reviewed in general. Background material, including other milestones and geological literature relevant to Yucca Mountain (about 300 pages), also will be provided for familiarization. A total of 48 hours is allotted for this Subtask.

2) Attend a 2-day meeting in San Antonio, Texas, beginning October 3, 1994, to discuss the principal objectives of the review with CNWRA and U.S. Nuclear Regulatory Commission (NRC) staff and other expert-panel members. A total of 20 hours, including travel time, is allotted for this Subtask.

3) Participate in a 3-day field trip to the Crater Flat area to examine basaltic volcanoes near Yucca Mountain, Nevada. The field trip will originate in San Antonio, Texas, beginning October 5, 1994, and end in Las Vegas, Nevada, the evening of October 7, 1994. A total of 24 hours, including travel time, is allotted for this Subtask.

4) Prepare a written report of recommendations to achieve the primary goals of the expert-panel review. Report will be due by November 23, 1994. A total of 40 hours is allotted for this Subtask.

APPENDIX E

AGENDA FOR PEER REVIEW OF CNWRA VOLCANISM RESEARCH

10/2/94 Sunday. Participants arrive from Hawaii(2), Eugene OR, Menlo Park CA, and Flagstaff AZ. Lodging at the Sheraton Fiesta Hotel in San Antonio.

10/3/94 Monday. Meet at CNWRA at 9:00 am for first day's discussions, focusing on what's been done in the research projects.

BH 9:00-9:20 - Introductions for Panel, CNWRA and NRC attendees

WP 9:20-9:30 - Management overview of the CNWRA and relationship to SwRI and NRC

BH 9:30-10:15 - What we're trying to accomplish with the review:
- Review objectives and approaches of CNWRA volcanism research.
- Improve CNWRA research scope and methodologies
- Evaluate CNWRA interpretations of available data, and explore alternative hypotheses

- This panel is convened to review CNWRA work. Need to emphasize that we are not trying to resolve the scientific controversies related to the YMR, or to evaluate DOE research.

- The format for the meeting is an informal workshop, with an emphasis on focused discussions rather than presentations and questions.

10:15-10:30 Break

CC 10:30-11:00 - Overview of the regulatory issues at YM site:
- Regulatory basis for research
- KTU's and their translation

11:00-11:30 Expert-panel caucus. Panel members:

- Elect a Chair for the meeting, who will ensure that sufficient time is allotted to address the review goals for each project. Chair will recognize questions from the audience and limit discussions if necessary to remain on schedule. Individual reports in November will be sent to the Chair, who will ensure that the reports are complete and add a summary statement if so desired.

- Panel members will decide the agenda for the rest of the meeting. The review panel will lead the discussions, focusing on what has been accomplished in the volcanism research programs.

If desired, BH can present an overview of the geological setting of the YMR 11:30-12:00
- Basic regional geologic setting
- Miocene caldera system, culmination of regional S-trend in B&R
- Neogene basaltic system
- Quaternary basaltic system
- Structural setting
- Outline of the geologic repository

END AM

CC 13:00-17:00 **Field Volcanism**: Consequences of volcanism on repository performance

Goals:
1. Identification of historically active analog volcanoes for YMR
2. Eruption dynamics from analogs and older deposits
3. Thermal & degassing effects at active & preserved volcanoes
4. Geophysical studies for resolution of subvolcanic features

Approaches:
1. Identify active basaltic volcanoes that have similar characteristics to YMR with respect to eruption dynamics and degassing-cooling. Continental arcs have suitable analogs to WGB and YMR.
2. Examine volcanological, geochemical, petrological and geophysical data to construct mechanistic and probabilistic models of basaltic volcanic eruptions. Data from active analogs and other WGB systems, including YMR.
3. Characterize direct and diffuse volatile degassing, extent of hydrothermal systems, and duration of these processes at active cinder cones. Examine available geological data to interpret these processes at YMR and WGB volcanoes.
4. Evaluate the utility of seismic tomographic and magnetic geophysical methods for the characterization of subvolcanic intrusions and structure. Examine subvolcanic structures for exposed WGB and YMR systems.

Products:
1. Literature review of the basis for using modern analogs for YMR volcanoes
2. Review of geophysical techniques applicable to basaltic volcanism issues
3. Fault-dike interactions (Semi 2/94)
4. Degassing and physical volcanology of Cerro Negro, Nicaragua, 1992 eruption.

Ongoing Research:
1. Degassing and soil-gas studies at Cerro Negro, Paricutin, and Tolbachik volcanoes
2. Granulometry studies at Cerro Negro, Paricutin, and Tolbachik volcanoes
3. Quantitative petrographic analyses
4. Petrology of the YMR basaltic volcanoes
5. Fault-dike studies at Fortification Hill, AZ

END PM

10/4/94 Tuesday. 8:30-12:00 **Volcanic Systems of B&R**
BH

Goals:
1. Relationship of Yucca Mountain to other B&R volcanic & structural areas
2. GIS of western Great Basin (WGB) volcanic fields & structure
3. Assessment of dating methods & uncertainty
4. Assessment of uncertainty associated with available data on WGB
5. Probability model development & testing
6. Conceptual magmo-tectonic modeling & uncertainties

Approaches:
1. Review available literature on B&R volcanism and tectonism. Put YMR into subregional context. Evaluate level of data available for magmo-tectonic modeling
2. Compile available data on B&R volcanic fields most analogous to YMR into GIS. Develop and test magmo-tectonic models, and evaluate completeness of available data.

3. Review methods of dating Quaternary and Neogene basaltic volcanic rocks, with emphases on limitations to dating techniques, expected uncertainties in dates, and dating studies of the YMR.
4. Review GIS data for accuracy and assess uncertainties in data, analytical methods, and assumptions in existing magmo-tectonic models for B&R.
5. Develop probability models that can account for the spatial and temporal heterogeneity observed in the eruptions of volcanic fields. Test available models and quantify uncertainties in model applications and results.
6. Develop geologic models relating the effects of regional and local tectonism with volcanism, to the YMR for the next 10,000-100,000 years

Products:
1. Literature review of B&R volcanism and tectonism
2. Compilation of data for Geographic Information System for the Cima, Big Pine, Coso, and Reveille/Pancake Range volcanic fields.
3. Review and assessment of dating techniques for Quaternary and Neogene volcanic rocks
4. Strategy to assess uncertainties in geologic models and data
5. Probability models in semi-annuals and Focus'93. (+JGR article?)

Ongoing Research:
1. Probability model development - incorporate spatial and temporal geological data.
2. Determine resolution of magmo-tectonic models and evaluate their application to the YMR for the next 10,000 years.
3. Ongoing GIS work on Death Valley, Yucca Mountain, Pisgah-Amboy-Dish Hill, and other fields TBD.

END AM

13:00-14:00 Expert-panel caucus to determine the scope of the afternoon discussions and to focus on specific issues. As a guide, discussions could focus on individual reviewer's recommendations to improve the scope of the programs, and what they see as critical issues for basaltic magmatism in the Yucca Mountain area:

14:00-16:00
- **Overall program goals.** General discussions on:
- Can the probability and consequence of future basaltic eruptions in the YMR be determined with low enough uncertainty to yield a solid determination of risk?
- Will the proposed research result in a capability to accurately evaluate this determination?
- Is the proposed research suitable to independently evaluate this risk?

- **Specific program goals.** For Volcanic Systems and Field Volcanism:
  - Critically review the objectives and approaches of CNWRA volcanism research and its application to licensing issues at the proposed Yucca Mountain HLW repository site
  - Recommendations to improve the research scope and methodologies, and investigate new issues that may not be part of the original research plans
  - Evaluate interpretations of the available data, and explore alternative hypotheses

16:00-17:00 CNWRA-NRC caucus to discuss preliminary issues raised in the review. Panel members may meet individually or as a group for further discussions.

10/5/94 Wednesday. Field trip to the Yucca Mountain area, Nevada.

Logistics: Travel to Crater Flat area and Lathrop Wells. **Southwest Airlines** flight 397 SA (8:45 a.m.) to LV (9:30 a.m.) direct. 14d $139, full fare $209. Other option**United** 204 SA (6:42 a.m.) to Denver, United 305 Denver to Las Vegas (9:31 a.m.). Stay at the Exchange Club motel, Beatty, Nevada (702-553-2333).

Arrive Las Vegas 9:30. Pickup 3 Jeep Cherokees and depart airport 10:30. Stop for Lunch supplies, on road to Lathrop 11:00. Arrive Lathrop Wells 13:00, drive to summit. Eat lunch.

Lathrop Wells:
- Summit: 13:30 - 14:00
  Major geographic and geologic features
  Crater morphology - primary?
  Eolian inflation and deflation surfaces, exposure dates = eruption ages?

- Drive to switchback area: 14:30 - 15:00
  Cone flank deposits
  Xenolith abundances and compositions

- Primary fall deposits at Quarry NE of buildings: 15:00 - 15:30
  Cone flank deposits - distribution of oxidation, lack of agglutination
  Fall deposits - interpret eruption characteristics. Xenos, cinder morphology

- Surge deposits on NW: 15:30 - 16:00
  Role of water in eruption - could this influence later stages?
  Interbedded fall deposits

- Scoria mounds on N & NE base of cone: 16:00 - 16:30
  Are these vents or pieces of cone walls?
  Morphology differences between flow units. Traps for eolian fines

Drive to Beatty (0.3 hr).

10/6/94 Thursday. Breakfast 7:00 - 7:45. Check out of hotel, purchase food and drinks 7:45 - 8:30. Drive to Steve's Pass 8:30-9:00.

BH **Steve's Pass:**
Local geology and stratigraphy of AFT's
Repository location
Basaltic volcanism
DF Structural Setting

Quaternary Crater Flat:

Little Cone SW: Quarry location 9:05 - 9:30. 15 min drive to Red Cone.
Deposit characteristics: Cinder morph, xeno abundances, bedding, agglutination
Energetics of eruption - comparison to Lathrop Wells

Red Cone:

9:45 - 10:45 Walk to SW dikes on top of Smith's older flows and possible vent. Discuss the polycyclic data.

10:45-11:45 - Walk SE to drainage, examine dike and flow contacts between RC units. Discussions on polycyclic eruptions, similar features from other volcanoes?

11:45-13:00 Return to vehicles, eat lunch

13:00 - 13:30 Summary discussions on differences and similarities between Quat CF volcanoes and LW, and other basaltic volcanoes. What is the potential of these volcanoes to disrupt a repository, and what sort of studies will best investigate this problem?

13:30 - 14:00 Drive to Steve's Pass then E to Pliocene CF exposure at 2948' hill

Pliocene Crater Flat: 14:00 - 15:30

General trends and exposures of 4 Ma basalts

Subvolcanic structures in near surface. How deep? Gradation of Breccia into agglutinate, bifurcation of dike

Dike swarm to S - 50-m-wide zone. Polycyclic or single pulsed eruption?

What volcanoes did these represent - LW or CF?

Summary discussions:

- What are the apparent unknowns in this system for the next 10,000 years?
- Research to address these unknowns, or better constrain the knowns.
- Where does YMR fit in reviewer's experience?

15:30 - 16:00 Return to Steves Pass. 16:00-18:00 drive back to Las Vegas. Pick-up lunch supplies for tomorrow, check into hotel (TBD), dinner 20:00.

10/7/94 Friday. Breakfast 7:00 check-out and depart hotel 8:00. Drive to Fortification Hill 8:00-9:00.

Overview of Fort Hill: 9:00 - 9:15

Dike-fault studies

Local geologic setting

Fort Hill geology

9:15 - 9:45 Drive to base of hill 786. Hike to exposures 9:45 - 10:15 [Hike is moderately steep (160' climb over 500') over loose colluvial slope. Option to examine dikes to south if this is too difficult for some]

10:15 - 11:30 Hill 786:

Multiple pulses of activity - textural variation. Multiple events or eruption pulses?

Dike - wall rock interaction; alteration, brecciation

Fault - dike interactions. Evidence for interactions with older structures or rock strength. Complex bifurcations of dike, characteristic of shallow (100 m) dikes?

11:30 - Depart Fort Hill for 13:00 return to Las Vegas airport for P. Delaney (& P. Lipman). Others may wish to examine southern dikes.

APPENDIX F

OVERVIEW COMMENTS FROM CHAIR OF THE REVIEW PANEL

SUMMARY AND OVERVIEW
1994 PANEL REVIEW OF CNWRA VOLCANISM RESEARCH

A review panel, consisting of Paul Delaney (US Geol. Survey, Flagstaff), Peter Lipman, US Geol. Survey, Menlo Park), Alex McBirney (Univ. Oregon), Steve Self (Univ. Hawaii), and George Walker (Univ. Hawaii), met in San Antonio, TX, and the Yucca Mountain region, NV, during Oct. 3-7, 1994, to evaluate current volcanism research at the Center for Nuclear Waste Regulatory Analyses and to provide suggestions for future research directions.

Panel members reviewed recent publications and administrative reports on volcanic hazards issues by CNWRA staff and other scientists active in the Yucca Mountain region, were briefed by CNWRA staff during two days of meetings in San Antonio, examined field relations in the Yucca Mountain region, and prepared independent individual reports on their observations and recommendations. Some key findings and recommendations, which were common to several or more of the individual reports, are summarized below:

STATUS OF CURRENT CNWRA VOLCANISM RESEARCH

The panel was favorably impressed with the thoroughness of the volcanism research undertaken by CNWRA staff; the approach is well planned and logical. The CNWRA staff are knowledgeable, energetic, and productive, although their efforts at times have been adversely impacted by overemphasis on administrative reports and repetitive program review. The legislative framework for the waste-repository licensing process also has created uneasy, and potentially antagonistic, relations between CNWRA and DOE research efforts, where communication, competition, and cooperation are the usual keys to resolution of scientific issues.

While not a specific charge for the panel, all the panel members developed major concerns during the field trip that the existing physical volcanology studies at Lathrop Wells and Crater Flat vents are inadequate, at least in terms of published data, to provide a defendable scientific framework for evaluation eruptive processes and recurrence rates. The panel members regretted that they were unable to interact during the field excursion with any of the DOE and other scientists who have been the most active workers on these vents.

MAJOR RECOMMENDATIONS:

In order to arrive at better probability estimates, research efforts should focus on (1) increasing the database of volcanic events, (2) improving the geologic evaluation of each event, and (3) maximizing use of tectonic and structural evidence. Some specific suggestions:

* Increase studies of basaltic volcanism in the Yucca Mountain region, including Miocene basaltic activity associated with waning of the ash-flow caldera complex. Drill-hole sampling of additional buried volcanic vents in

Amargosa Valley, currently inferred from geophysical data, would be desirable to determine age and volcanic character.

* Augment physical volcanology studies of the Lathrop Wells and Crater Flat centers in order to improve understanding of eruption dynamics and vent locations. Evaluate available granulometric data (e.g., scoria size, density, vesicle types) on basaltic tephra associated with Pliocene and more recent volcanism in the Yucca Mountain region, generating additional data where needed, and making comparisons with most suitable analog eruptions to constrain probable eruptive intensity of any future activity in the vicinity of the repository.

* Augment effort to document other young mafic centers in the Basin & Range that provide well-preserved analogs, while rigorously evaluating validity of comparisons with historically active proposed analogs.

Productivity and scientific credibility of the volcanology research at CNWRA could also be enhanced by several management initiatives:

* Prioritize project goals, focusing more effort on most urgent tasks. Reduce project load of administrative reports and technical reviews, generating additional time to complete in-depth studies in Yucca Mountain region and analogs elsewhere that can be written for publication in peer-reviewed journals that reach a wide scientific audience.

* Augment scientific interactions with tectonics and hydrologic study groups at CNWRA, LANL, and USGS.

* Encourage organization of an invitational field workshop focused on physical volcanology, bringing together DOE, USGS, and Nevada project scientists with uninvolved volcanology experts, to evaluate existing conflicting hypotheses on volcanic processes at Lathrop Wells and Crater Flat.

Additional effort could also be directed toward augmenting the geologic perspectives of administrators in NRC and DOE as well as the broader public. The earth is not an engineered material, and our access to it and understanding of it will continue to be imperfect. Quality assurance methods are better suited to engineering objectives and to generation of routine data than to encouraging the most reliable interpretations of necessarily imperfect geologic data using cutting-edge methodologies.

Prepared by P.W. Lipman,
and reviewed by panel members
November 15, 1994

APPENDIX G

INDIVIDUAL EXPERT-PANEL MEMBER REPORTS

CNWRA Volcanism Research Review Panel, October 1994

Comments by:

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Some of the issues addressed here probably lie outside the mandate of our Review Panel, offering instead my outsider's view of volcano-hazard studies in the Yucca Mountain region. These larger concerns, I think, should also be of fundamental interest to the CNWRA.

General

The NRC is being well served by the CNWRA volcanism research group. The program is well planned, although overly bureaucratic in the sense that too many reports have been written to document a worthwhile but quite finite set of results. Yet, judging from those written materials provided to us and from the oral presentations and leadership of the field trip, Chuck Connor and Brittain Hill are informed and motivated workers, and certainly opinionated; they are fully capable of undertaking independent research and of judging results generated by others concerning volcanic hazards near Yucca Mountain.

Although the analogy between the Yucca Mountain volcanoes and Cerro Negro, Paricutin, and Tolbachik is stretched, I heartily endorse the methodology and the need for familiarity with active volcanic processes. Monitoring of and experimentation on historic volcanoes can provide wonderful temporal information not discernible on volcanoes that are too old to have been observed during eruption. In this regard, Chuck and Brit fill what appears to be a void within the combined NRC/DOE research program. Unfortunately though, there is simply no direct modern analog of the basaltic volcanism that has been pervasive across the interior western U.S. throughout the Tertiary. The effectiveness of analogs rests upon identification and characterization of processes and this is a much more difficult undertaking.

The need to eventually characterize all hazards and their consequences as parameters within a probability model is staggering in its dimensions and implications. Substantial progress has been made toward quantifying those hazards. As discussed below, Chuck has an excellent perspective on the problem. Yet, in the end, the earth is not an engineered material and our access to it is restricted. Virtually all geophysical data sets are nonunique in their interpretation and our understanding of physical processes is likely to remain rudimentary when judged by the complexity of what we routinely observe. I suspect, therefore, that many judgements concerning the proposed waste repository at Yucca Mountain will be made by consensus, by intuition, even by the seat of the pants, and perhaps by dire necessity.

Field Volcanism

As mentioned above, the analog studies are both valuable and limited in their usefulness. Moreover, disruption of the repository would be as much by intrusive processes as by eruptive. Cerro Negro and Tolbachik are components of large volcanic fields where there is evidence for, or suggestion of, high-level magma reservoirs. Comparable reservoirs are probably absent beneath Yucca Mountain. Looking ahead, I do not have a clear picture of where the research on these volcanoes will go; the observations do not yet seem to stand on their own as results that could be written up for publication. Nonetheless, I was intrigued by the durations of high-temperature fumarolic activity after cessation of eruption. There are a number of vent-related processes that could account for this. There are also features exposed along many dikes that could produce the same effects. I doubt a unique answer will emerge.

Examination of eroded volcanoes and subvolcanic complexes can also provide crucial information not otherwise available. A particular area that might be of concern to the NRC is the size of dikes in the shallow subvolcanic environment and the processes that occur around them. Some of the present focus upon cinder-cone alignments and upon coincidence of vents with normal faults should eventually turn toward a characterization of dike length, width, extent of brecciation, and occurrences of "necks" and "plugs" as a function of depth. It is my impression, although hardly one I could prove at the moment, that most basaltic single-vent eruptions in environments where the magma must rise from its source depth are fed by dikes that lengthen considerably with depth. Let's guess a kilometer of length per kilometer of depth. This measure will eventually form the appropriate "area" term in the probability models. I wish I had visited the dikes and sills near Paiute Ridge with Chuck, Brit, and Linda Kovach on the Saturday after our field trip ended. There are many localities throughout the western U.S. where useful data could be collected; the Rio Puerco near Mount Taylor, New Mexico, the western Grand Canyon, the San Rafael dike-and-sill swarm, southern Utah, and Hopi Buttes, northern Arizona, come immediately to mind.

I was struck by the narrow focus of our discussion when viewed against the backdrop of the spectacular history of Tertiary volcanism nearby, as summarized by Peter Lipman. In so far as we don't understand the conditions and time that give rise to brief episodes of basaltic volcanism, physical and statistical models of the youngest basaltic volcanism should be consistent with this broad history. This is why certain results implying that volcanism is presently "waxing" seem to defy logic, at least to me. Are there reasons to believe that the Pliocene and younger volcanism near Yucca Mountain is fundamentally different than its nearby predecessors? Results that rely only upon the sparse data of the past 1.6 Ma, or the past 6 Ma, may suffer from losing sight of the forest among the trees. Certainly, the underlying igneous system, or systems, didn't set its clock in this simpleminded fashion.

Volcanic Systems

Compilation of data into a GIS format. The possibilities of GIS systems are much less than usually advertised. At present, ARC/INFO is simply not a research tool. It seems to be designed with data-base storage (not access! and certainly not manipulation) and standardized menu-driven displays in mind. It is not suited to "what if" queries and I doubt that many or even any new discoveries are going to be made simply by superimposed display of disparate data sets. It seemed to me that Chuck and Brit know this and are structuring their efforts accordingly. I am less certain that the CNWRA, and perhaps the NRC, recognize these limitations. It may be very important for QA that data used by the CNRWA be put there; to do so under the banner of "research" is, conceptually, a mistake. Does all of the Basin and Range data, especially information on other volcanic fields, really need to be in this format to assure that DOE's license application will be properly evaluated? I would hope not. Chuck and Brit seem to be in the early stages of digesting many of these data; I don't know what will come out that effort. I suggest that this project will do better if it focuses toward more traditional methods and uses GIS data only where it can be supplied with little effort or cost. In the end, it seems that this project should concern itself with, for instance, the abundances, styles, and durations of basaltic volcanism that persists after silicic centers shut down, or eruption frequencies and vent geometries of basaltic fields in the western US, or basaltic dike abundances and sizes in the western US. These topics do not require a GIS; probably, they would proceed more quickly without it.

Probability models. This may remain a contentious, and therefore important, topic for quite some time. Chuck's presentation of this material was very good, almost certainly the most sophisticated material that we had to digest. I hope he takes this work through to publication in a first-class journal; this may be a good strategy for bringing some of the problems posed by the Yucca Mountain site into a more public and accessible format. I spent some time trying to understand not only what Chuck has done, but some of what's in the literature as well. Although hardly comprehensive, I don't think there is a paper that "rings true."

I have the impression that Ho's work using the Weibull model, apparently the most sophisticated analysis to date, is seriously flawed as applied to volcanoes and just plain wrong as applied to those near Yucca Mountain. First, it seems that the model behavior is dependent upon a selection of "time zero" when it should be independent of it. If the model were applied, for instance, to mechanical glitches of a certain type of machinery, time zero is obviously the date of manufacture; once put to use, the machinery *must* eventually fail unless taken out of service. Other materials, sheet rock, for instance, will not fail if they survive their initial manufacture, distribution, and installation. Ho (1992, p. 356) chooses the beginning of the Pliocene and the onset of the youngest volcanism, 6.0 and 1.6 Ma, respectively, as "time zero" for his pair of calculations; these ages, particularly the first one, have no physical significance that we can attribute to the underlying igneous system. Yet, if we choose different time zeros, we obtain different results. Second, reflecting our ignorance, I would argue that a robust method should give the same answer with time set backwards as well as forwards. Waxing forward in time should be no different than waning backwards in time. If time were set backwards and we ran the test back to the beginning of the Pliocene, would we have both a decent probability for the older eruptions at Yucca Mountain and the same conclusions about the next ten thousand years? It doesn't look like that could come out of the Weibull model; it can allow waxing or waning, but not both. Third, I would be concerned about *any* model that *extrapolates* as a power of time when there are so few data.

Fourth, look at the ages Ho uses (1992, p. 356), in Ma: 3.7, 3.7, 3.7, 3.7, 2.8, 1.2, 1.2, 1.2, 1.2, 1.2, 0.28, 0.28, 0.01. These are treated as $n_0 = 13$ independent data for the 6-Ma calculation; $n_1 = 8$ for the 1.2-Ma calculation. At the very least, the "clustered" events are not independent and to include them, as Ho and others have done, requires an estimate of their covariance. There is a strong case to be made that the four 3.7-Ma events should be one eruptive sequence, as well as the five 1.2-Ma and two 0.28 Ma events, and that the last event should, of course, be 0.12 Ma. After including the 4-Ma event in Amargosa Valley and the 4.6-Ma event at Thirsty Mesa, this would give $n_0 = 7$ and $n_1 = 3$. (It's sad that at least three other vents are known to exist, in Amargosa Valley, and nobody knows their ages.) The geochemical and petrologic evidence to support this view is compelling. Vaniman and others (1982) show that the Lathrop Wells, West Crater Flats, and East Crater Flats volcanoes are geochemically distinct, with variations within each center appreciably smaller than those among them. I would guess that this finding could be extended to include the other basaltic centers as well. These are each the result of discrete *igneous events*, comprised of one or more eruptions and an equal or greater number of intrusions. The concern is the probability that another igneous event will commence during the next 10 ka; whether it is comprised of a long eruption sequence from single or multiple vents is only relevant if indeed something gets started at all. The upshot here is that, fifth, Ho uses a "worse case" scenario rather than one that could be defended as the most realistic and relevant on geologic grounds.

I have the impression, both from the paper CNWRA 94-015 and from Chuck's presentation, that the near-neighbor nonhomogeneous Poisson model postulates that the next occurrence of igneous activity will be within a distance from the previous site with a probability that is proportional to the inverse square-root of time since the last activity. This assertion is testable. My quick plotting of the data doesn't appear to support it. Is there an "optimal" choice for this proportionality? If that relation can't be supported by the data, what are the alternatives?

For what it's worth, here's my way of identifying the volcanic hazard at Yucca Mountain. An average is one igneous event per million years, giving a chance of the next intrusion/eruption at $\sim 1\times10^{-6}$ per year. I guess an average affected area around a dike at a few hundred meters depth of, say, 0.5 km × 5 km. The Yucca Mountain volcanism "province" is within an area of ~100 km × ~75 km, so the chance of being within the affected area of the next event is $\sim 2\times10^{-4}$ per square kilometer. There are, let's say, 25 square kilometers of proposed repository, giving a chance of 5×10^{-3} that the next eruption will intersect it. I then get 5×10^{-5} as the chance for trouble at that site during the next 10 ka.

It is important to confirm that the maximum reasonable durations of activity at each center are small in comparison to the intervening repose; as long as we are not still in the Lathrop Wells eruption sequence, then it isn't relevant to the probability of the next event whether or not it will be comprised of numerous phases spread over some number of years.

Both the NRC and CNWRA seem to have the ability to contract with specialists. It might be very useful to identify a statistician who can handle these problems and further help evaluate Chuck's work.

Field Trip

Britt and Chuck were well prepared, guiding us to localities, providing background information and copies of relevant material from the literature, and otherwise leaving us to come to our own conclusions and to start our own little arguments and discussions without prompting. It was useful to have Gerry Stirewalt and David Ferrill along to provide a regional tectonic backdrop and to hear Peter Lipman's outline of the silicic volcanic geology and identification of various lithic fragments. As discussed above, it was especially useful to hear from George Walker and Steve Self their reconstructions of the eruptive style and chronology based upon the character of the deposits and the type and extent of alteration. It seems that such studies, which rely upon granulometric measurements of tephra, cataloging of lithic fragments, mapping of alteration, and analogy to modern volcanism, have only been done in a preliminary fashion. Similarly, I was surprised that the only detailed map that I saw was of the Lathrop Wells volcano. Certainly, the others warrant comparable attention.

Lathrop Wells This cinder cone, being the youngest, was the best exposed among those visited. Nevertheless, I was struck that the top ~0.5 m of tephra is everywhere indurated and pervaded by wind-blown sand. Structures that seem to be common in modern cones, especially fractures that form during ubiquitous slumping and adjustment of the cone, are absent. Where the inner slopes of the Lathrop Wells cone reside at angles much less than repose, many modern cones have oversteepened inner walls, owing to the strengthening effect of lavas congealed at the vent. The deposit mapped by Crowe and coworkers as an early base-surge deposit is clearly the remains of a larger deposit that has been stripped away. Taken together, I doubt that the present tephra and scoria surfaces should be accepted as originals.

The Lathrop Wells rocks appear typical of a "monogenetic" basaltic volcano; by analogy to modern eruptions, the whole thing could have been over in months, years, or perhaps as much as a few decades. Although the eruption almost certainly began along a fissure, effusion localized, as it usually does, to the position of the cone. Many cinder-cone eruptions issue from fissures that aren't long; the dikes beneath, however, probably lengthen considerably with depth. I doubt that the fissure could have been much longer than the present extent of the eruptive deposits, even though subsequent alluvial deposition could have buried it. Probably, production of tephra, much of it now buried, and lava proceeded contemporaneously during much of the eruption. It's notable that the east side of the cone is the lowest. The presence of scoria mounds on the adjacent flow suggests that the east side slumped and was carried off on the lava flow at least once during the eruption. The apparent lack of vent structures on and near the scoria mounds, their presence along the margin of a flow lobe, on the one hand, and along the east base of the cinder cone, on the other, strongly suggest that they were rafted into place. Given the way lava flows solidify on the surface and remain fluid and mobile beneath, the flow could have been, probably was, fed from low in the cone at the same time that the final fountaining was rebuilding the cone towards its final shape. I believe that if there had been a wholly separate eruption, as might even be construed from Champion's maximum duration of 100 years estimated from SV, there would be structural evidence in the form of overlapping cones, a linear vent cutting the lavas, perhaps even a less coherent shape to the present cone of the adjacent lava flows.

I did not look at the flow-boundary contacts of the oldest flow unit identified on Crowe et al.'s preliminary map. Outcrops that appear to have been crucial to their interpretation have been destroyed by quarrying operations and infilling of pits and trenches. Lacking these, it would be interesting to see the complete tephra section west of the cone to establish the character of the earliest deposits. It is notable, though, that none of Crowe's many coworkers are volcanologists experienced with active processes. I'm confident that at least some of these groups findings concerning soil profiles, geomorphic degradation, stratigraphic succession, cone shape, flow morphology, and lithology would be modified by input from workers experienced with active basaltic volcanism.

Western Crater Flat The two of these cones we visited were much degraded in comparison to Lathrop Wells. At both Little Cone and Red Cone, I had the impression from their lobate form in plan view that the flow margins are nearly at the present exposures. If so, it would be easy and useful to verify. At Red Cone, the proximity to flow lobes of structures mapped as dikes is suspicious, as is their lack of a nearly uniform strike. These features are much more likely linear "push-ups" formed by lava upwelling along weaknesses at the flow margin. Lipman found some ropy pahoehoe textures on a surface of one of the "dikes." I did not visit any of the scoria mounds scattered across the lava flow and mapped as vents. Their lack of alignment and the apparent absence of agglutinate, remnant vent structures, and identifiable flows that can be traced from them, suggests that they also were rafted from Red Cone during its eruption. It appears that Red Cone itself is a single vent.

The alignment of these cones and the possibility that the feeder dikes do not parallel the alignment combine to form the nearest defensible scenario of "polygenetic" volcanism that I saw near Yucca Mountain. Even here, however, there seems to be a distinct possibility that the best isotope and paleomagnetic determinations of relative ages will turn out to be indistinguishable among the cones. If so, there would be a compelling argument for magma ascent along one strike (NNE) at depth feeding shallow dikes of a different preferred strike (N). This would be pretty neat.

Eastern Crater Flat This was the most eroded among the localities we visited. It also seems that it was probably the largest eruption among those them, as measured by lava-flow area. The northern extent of the flow is uncertain, being buried by alluvium.

We walked along the dikes for about a kilometer. I had the impression that, along most of this length, the present exposure surface is no more than several meters beneath the original. Brit pointed out a locale where a flow traces directly into a dike segment. The dikes are well exposed and were interesting to examine because they cut the volcanic deposits that they fed. Judging from the steep plunge of intersecting dike segments, it appeared that the dike was propagating more nearly vertically than horizontally. Although there appeared to be two dikes arranged side-by-side along some of this length, it is more likely that the magma came up along different sides of small graben-like structures that formed in the loosely consolidated tephra. Such grabens, often poorly and irregularly formed, are common in Hawaii. As further evidence, at one locality, a dike segment turned easterly from its western position and ended up on the east side. In places, it looked as if the dike swelled out and I think these would have been seen as small lava ponds if the eruption had been observed. This would be a nice place to make a map, a project that might be a necessity if the assertion were to develop that their are two dikes or that the dikes are significantly later than some of the other deposits.

We didn't walk to the northern vents. Judging from their proximity and from the alignment along the general strike of the dikes, I would guess that all of the volcanics were erupted in a single sequence. Finally, the large fault scarps that cut these flows would seem to offer fantastic rates of deformation. I hope somebody has been studying them.

Fortification Hill The dikes we visited, those just south of Fortification Hill, seem to have propagated subvertically. There was nice evidence of dike-segment interaction, which gives information about relative dike ages based upon the mechanical interaction of the younger with the older. At the locality Chuck showed me, where a small low-angle fault is cut by a dike, I did not feel that there was evidence for interaction with that fault, although an outcrop map would certainly resolve the question. The fault was of such low angle, that it's application to those near Yucca Mountain is questionable.

These dikes were typical of many, many others in having wall rocks that are apparently pristine, except for discontinuous pockets of breccia along the contact, usually only a few centimeters thick, that contrast with pervasively altered basalt of the dike itself. In this case, it appears that calcite fills vesicles and vugs; I would guess that some zeolites and/or chlorite would show up in thin section. Can cooling dikes serve as "heat pumps" to suck in groundwater and send it buoyantly to a vent above? The basalt would have to be vesicular and/or create fractures and voids as it cools; there's certainly evidence for this. Hot water or steam in a permeable dike beneath a vent could have a pressure gradient of, say, 100–900 $kg/m^3 \times 10$ m/s^2 = 1–9 MPa/km; groundwater resides at 10 MPa/km. At any given depth below the water table, if it's negligibly shallow, there would be a substantial pressure difference sucking groundwater towards the dike and driving it upward. This flow, in turn, could keep the host rocks adjacent to the dike cool and, perhaps, unaltered at the same time as providing fluids that would almost certainly introduce a disequilibrium to the cooling basalt. There ought to be some geochemical tests of the alteration mineralogy to provide a handle on this. It is a radically different scenario than either conductive cooling or even hydrothermal circulation within groundwater aquifers. It's intriguing, an attractive hypothesis.

Final Comments

I applaud the CNWRA for insisting that their work be open and subject to criticism from independent specialists. I also thank Chuck and Britt for preparing so much material. I learned a lot.

It is not clear to me what balance should exist between efforts on the volcanism near Yucca Mountain and on "analog" volcanism, both modern and ancient. If Chuck and Brit were to focus upon the former, would there be an improper infringement on the responsibilities of DOE personnel to present their own case? I hope not. The perceived need to keep DOE- and NRC-affiliated research separate runs counter to normal scientific give and take and may contribute to an unnecessarily polarized environment.

Many of the basaltic volcanoes of Yucca Mountain region appear to lack geologic maps on a topographic base that detail flow and tephra units, flow structure, vent geometry, and occurrences of fractures, if present, that could be related to fissures. Such maps compiled onto traditionally serve as the base for all subsequent studies.

There does not appear to have been much use of granulometry, alteration mineralogy, and other methods, to help reconstruct eruptive style and sequence. (There is a 1983 report partially devoted to this topic with Steve Self, who hadn't even been to Lathrop Wells at the time, as a coauthor.) Certainly, such an avenue, even if pursued at Cima or elsewhere, including a thorough verification by comparison with data collected at a modern volcano, would be exciting and would give the NRC an excellent background study. Along similar lines, a review of the literature and perhaps some focused research could document variations in magma chemistry during a single modern eruption that are as varied as those found among deposits of the volcanoes near Yucca Mountain. A map of the two vents at Cima that are spatially coincident would, I bet, have distinct differences when compared to a map of Lathrop Wells.

In the long run, and from an outsider's perspective, the quality of advice given to the NRC by the CNWRA is proportional to the acceptance within the earth-science community of Chuck's and Brit's work. This is best established by publication in refereed journals and presentations at major conferences and meetings. The many reports that have been written to date may satisfy contractual obligations; most of them will not necessarily establish methods and conclusions that are broadly accepted, particularly to critics that are likely to surface eventually. On the other hand, I recognize that the NRC seeks information that comes from little more than a summary of existing literature. In the end, everybody will be ahead if the staff of the CNWRA has a reputation as publishers of first-class research. A great deal of effort and time is required to take even a modest piece of research through to publication. It is time well spent.

This brings me to the final, final comment: focus. I doubt that Chuck and Brit can eat during the next few years all that is on their plate if full digestion includes bringing the work to publication in refereed journals. It would help if some of the administrative and technical reports could be formed as publishable manuscripts with a cover document outlining recommendations and findings that are specific to the needs of the NRC. Chuck and Brit should decide the topics that warrant publication during the few years left on the existing contracts and should prioritize their work accordingly.

1994 PANEL REVIEW OF CNWRA VOLCANISM RESEARCH, Oct. 3-7, 1994

Impressions and recommendations, by P. W. Lipman

GENERAL IMPRESSIONS

My over-riding impression is that CNWRA volcanism research is well planned and staffed by able young scientists who are highly enthusiastic about their work, are well-founded in modern volcanologic concepts, and should able to provide critical expertise for review and independent evaluation of the volcanic-hazard issues that might impact nuclear waste-disposal plans at Yucca Mountain and elsewhere.

The CNWRA staff prepared superbly for the panel meeting in terms of advance materials, logistics, and material presented at the meeting and field trip. Without input from CNWRA on volcanic hazards issues, the NRC would need to generate such expertise from elsewhere in academia or government, and comparably sustained focus and dedication to NRC needs might be difficult to obtain.

Discussions during the panel review have generated several broad concerns that seem important to note, however, even though some of these may be beyond the scope of the review panel's charter or the capability of CNWRA to mitigate:

(1) Division of responsibility between DOE and NRC for interpreting the significance of volcanic (and other) hazard issues at Yucca Mountain may be generating redundancies and gaps in the supporting research that could adversely impact the timing and even the ultimate success of the repository evaluation process. Over the past 10-15 years, responsibility for studying volcanic-hazard issues at the Yucca Mountain site appear to have primarily resided with a small scientifically specialized DOE staff, and their work to date seems to have been sustained without rigorous independent review. The NRC and CNWRA roles are apparently restricted primarily to developing independent broad expertise that will be needed to evaluate the DOE work at the time of a licence request, rather than generating independent framework data for the Yucca Mountain region. The intensity and breadth of review generated at this time for the relative small and recently initiated CNWRA volcanology projects may exceed that given to the long-duration volcanic-hazard site-characterization studies by DOE scientists and their associates in academia and the USGS. My brief observations at Lathrop Wells and Crater Flat cones give rise to concern that the basic volcanologic studies to date may have been inadequate to define volcanic vent locations correctly and may have misinterpreted the sequence of eruptive activity. Without a valid physical-volcanologic understanding of eruptive and emplacement processes for the Crater Flat basalts, the sophisticated morphologic, soil-development, geochronologic, paleomagnetic, petrologic, and geochemical studies that have been undertaken there are likely to be based on inadequate foundations.

(2) The amount of time and paperwork devoted by CNWRA volcanology staff to preparing project proposals, writing progress reports, drafting interim literature-review products, and providing written and oral input to reviews by NRC staff and its advisory committees likely is adversely impacting desirable levels of research progress in the two relatively small and recently initiated volcanology projects.

(3) The two CNWRA volcanology project are concurrently undertaking a large number of diverse studies, and run the danger of being unable to make adequate progress on any of these without a clear sense of priorities. Some suggestions for prioritization are embedded in the comments that follow.

(4) On-site examination of field relations by the present panel members, and hopefully others in the future, provides an especially effective format for reviewing prior work, providing suggestions for alternative methodologies, and identifying issues that deserve further study. Extreme concern for avoiding "appearance of conflict of interest" may be depriving the important volcanic-hazards work in the Yucca Mountain region from interaction with some of the best available expertise and may lead to undesirable "reinventing the wheel," duplication of effort, and loss of scientific credibility.

FIELD VOLCANISM PROJECT:

The primary focus of the CNWRA field volcanism project is to study active analogs for the basaltic cinder-cone volcanism that has occurred in the Yucca Mountain region, in order to assess intrusive extrusive eruptive processes that could disrupt the waste repository. Even though there are substantial difficulties in obtaining truly comparable analogs, I am impressed that analog studies are a valuable part of the overall CNWRA volcanic research: (1) even imperfect analogs provide insights into processes that cannot be obtained solely from study of ancient analogs, (2) the search for and evaluation of analog comparisons will likely generate improved understanding of volcanic activity in the Yucca Mountain region, and (3) all volcanologists working on ancient systems need the opportunity to devote a portion of their effort to active systems in order to broaden their analytical capabilities. This last point is especially critical for younger researchers, such as those that staff the CNWRA projects.

The project work plans and goals for this project are praiseworthy and ambitious. My most serious concern is the appearance of splitting limited resources among so many topics, impeding and diluting progress and impact of the project.

Secondly, several concerns emerged during the review, and apparently in earlier reviews as well, concerning the validity of the selected analogs in comparison to the basaltic cones in the Yucca Mountain region, especially in terms of arc-volcanic vs transtensional tectonic settings, sites of repeated nearby intrusion and extrusion vs more nearly monogenetic settings (eg, along Tolbachik rift zones), phenocryst-rich vs crystal-poor magmas (not only phenocrysts, but also microphenocrysts and microlites) with implications for contrasting viscosities and explosivity, and contrasting amounts of crustal assimilation (especially Paricutin). The arc-volcano analogs may be more crystal-rich, leading to more explosive eruptive behavior and more widespread dispersal of tephra. Especially critical for evaluating areal extent and duration of post-eruption thermal activity will be the presence/absence of a sizeable upper-crustal magma reservoir, seemingly more likely in arc-volcanic settings because recurrent eruptive activity as evidenced by multiple overlapping cones, rift-zone dikes, and proximity to larger volcanoes. Another potentially critical issue that should be addressed as carefully as possible in active-analog studies is the depth to, and role of, any hi-level groundwater.

I was impressed at the case made by other panel members for alternative appropriate historical analogues, such as Heimey in Iceland. Also, much could be learned about relevant eruptive processes from detailed study of the tephra from young prehistoric basaltic vents that are closely comparable in setting to the Yucca Mountain region, perhaps selected sites from the volcanic fields that are being systematized in the GIS database for the Basin-Range region. We need to know more fully what is typical and what is atypical about the Crater Flat volcanoes.

A intriguing problem that came up during discussion was the difficulty being encountered in determining water contents of the Crater Flat ejecta by melt-inclusion analysis. In recent years, melt inclusions have yielded excellent data for tholeiitic and arc basalts from many regions; are there good inclusion data for any alkalic basalt suites comparable to Crater Flat, or is there some intrinsic petrologic character of alkalic basalts that melt inclusions are poorly developed (and if so, why)?

I don't believe in our discussion we adequately reviewed the potential for improved resolution of subvolcanic features by geophysical methods. From what I heard, the possibilities of detailed ground-based magnetic profiling seem intriguing, but the resolution of seismic tomography seems less clearly demonstrated, especially if the targets are 1-2 m basaltic dikes, rather than discrete upper-crustal magma chambers. If the depth of alluvial fill in Crater Flat remains poorly constrained (as we were told), then improving on this would seem a higher-priority and more amenable geophysical priority.

Overall, I give this project high points for effort and productivity, but worry that perhaps a larger proportion of the finite resources should focus on characterizing the eruptive processes at basalt vents in the Yucca Mountain region and analog basalts nearby.

VOLCANIC SYSTEMS PROJECT

This CNWRA project seems only in its early stages, despite apparently having been initiated before the field volcanism project; the rate of progress perhaps has suffered from changing staff, goals, and methods, as well as from the ambitious focus on GIS compilation. This is a critical volcanology project for effective interaction with the tectonics team.

The GIS Basin-Range compilation has great potential to aid comparisons between Yucca Mountain and other B-R volcanic areas, and considerable progress has been made in compilation of the framework data. I have some concern, however, whether specific issues to be addressed have been formulated sufficiently clearly that the data are being compiled in the most appropriate formats. Another major issue concerns evaluating whether adequately comparable data are available for the different volcanic areas being compiled, and whether the type and quality of available data are adequate to provide valid comparisons with the intensely studied Yucca Mountain region and to provide valid insights for the most critical issues.

For example, just compiling mapped surface faults may be inadequate to define the major structural boundaries between mountains and basins that can provide an appropriate basis to test correlations (or lack thereof) between basaltic vent clustering and structural lows (the principal basin-bounding faults are commonly concealed by surficial basin fill). Are volumes of eruptions from individual vents adequately known, so that the cumulative volume of activity can be evaluated as a function of elevation above the bottom of the structural trough for individual volcanic clusters?

Another important question, that I would hope could be tested within the framework of a broad regional database is whether clustering of basaltic vents increases or decreases as a composite basaltic field matures. If a consistent pattern of changing dispersion with time were to emerge, the relation would have obvious implications for probability analyses of basaltic volcanism breaking through the repository site, which lies near but outside the NNW-trending zone of Plio-Pleistocene activity along the Crater Flat-Sleeping Butte locus.

Similarly, comparisons of raw petrologic data among basaltic fields may document variations in source region more compellingly than providing insight into varying degrees of crustal interaction--potentially a more important influence on eruptive mechanisms and near-surface intrusive processes. In the study areas what can be said about the presence/absence of upper-crustal magma chambers during the culmination of basaltic volcanism: a critical issue, but one that requires interpretation beyond data compilation? When Q/A issues become a dominant concern, do they potentially become a pitfall and barrier to pursuing interpretive objectives, so that the product may have assurance of data quality, but without adequate evaluation of relevance and significance, reliability of interpretations, or even whether useful interpretations are generated?

The project effort to improve statistical models of eruptive recurrence probability for the Yucca Mountain region is impressive and laudable, especially because previously published models seem to have been so simplistic. Certainly, the evidence for clustering of vents in Crater Flat and elsewhere in the western Basin Range is overwhelming and must be factored into any statistical approach. Serious common-sense problems remain, however, in applying the probability models: is the data set sufficiently robust to provide needed resolution, how large a region should be modelled (inferred degree of relation to earlier caldera magmatism is critical), and whether the data set is flawed by incomplete sampling of older events for which the record of activity may be conceal by younger fill in Crater Flat and nearby basins? Another probability issue is whether a regional tectonic factor may not be critically important and need to be factored into an overall hazard evaluation (see my separate comments on regional B-R setting). Finally, I as a panel member am not qualified to provide any sort of rigorous evaluation of the statistical methodology; I'm not sure any of the panelists would feel up to this, and some sort of external review by a consultant statistician might be desirable if the probability modelling is to figure large in the hazard evaluation. Perhaps submittal of results to a well-regarded refereed journal could be adequate.

The completed project reviews of evolution of the B-R province and of geochronologic methods, while undoubtedly helpful in directing the focus of PIs while engaged in upgrading their familiarity with these topics, have not led to truly innovative thinking on these topics, provide no basis for formal publication, and suggest an overly narrow focus by higher-level management on "deliverables." Such formal reports for review efforts divert considerable time from other potentially rewarding research activities.

REGIONAL VOLCANO-TECTONIC SETTING, THE YUCCA MOUNTAIN REGION

I include this topic as a separate heading, because it is the aspect of the project work for which my expertise is perhaps the most broad among panel members, and one that I believe would benefit from additional effort by CNWRA volcanism research.

An apparent weakness in the present work is evaluating the broad time-volume-process relations for basaltic volcanism in the Yucca Mountain region, in relation to preceding magmato-tectonic events along the Walker Lane zone of transtension, and in relation to concurrent Miocene evolution of the SW Nevada volcanic field. I doubt that the origin of the Pleistocene basalts eruptions of the Yucca Mountain region can be adequately understood, or the probability of future volcanic events evaluated, without such a framework.

Eruption of approximately 5,000 km^3 of silicic magma in giant ash-flow sheets associated with caldera subsidence of source regions implies generation of a major upper-crustal batholith in response to upwelling of voluminous mantle-derived basalt. Existing estimates of basalt flux for the post-caldera period (10 Ma - present) neglect the voluminous basalt that likely ponded in crust or mixing with the solidifying subcaldera batholith, and probably underestimate the volume of 10-7 Ma basalt that has been largely concealed in basins (but is locally penetrated by drill holes in Crater Flat and Yucca Flat). It seems unjustifiable to me that published interpretations of basaltic volcanism of the Yucca Mountain region include 8-10 Ma basalts on Pahute Mesa and Paiute Ridge but exclude contemporaneous activity of much larger preserved extent and volume at Skull Mountain and Dome Mountain, both of which are closer to the repository study area. Determining whether the Plio-Pleistocene activity at Crater Flat and Sleeping Butte represent waning of the more broadly geographically distributed Miocene activity, or a discrete new magmatic episode, has important implications for hazards evaluations.

From presentations and questions, I also recommend that the volcanology (and/or tectonics) group consider devoting additional effort to evaluating the status of knowledge of the deep structure and lithologies present in the Crater Flat graben. In conjunction with the tectonics project, such data are needed to interpret the significance of variable xenolith quantities and rock types present in the cinder-cone ejecta. Evaluation of depth to basement in Crater Flat-Amargosa Valley graben system would also provide key data for relating locations of basalt vents to structural relief and for evaluating whether the west side of Yucca Mountain represents the present margin of a the Walker Lane, and for comparing the rates of volcanism in relation to tectonic extension.

IMPRESSIONS OF YUCCA MOUNTAIN REGION (field trip)

The opportunity to spend two days in the field, examining the basaltic vents and associated lava flows in the Crater Flat area, provided an eye-opening opportunity to compare modern concepts of basaltic eruptive processes with these much-studied rocks and to develop a much improved personal framework for evaluating published reports of recent work aimed at evaluating the possibility of volcanic disruption of the repository. The opportunity was especially welcome because I mapped large parts of the Yucca

Mountain region and made early petrologic studies of the repository volcanic sequence as my initial USGS assignment in the early 1960's, but had not been in the area for 25 years. The early work provided me both with considerable familiarity with the regional geologic problems, but also some detachment from more recent controversies.

Perhaps the most valuable overall lesson from the field trip was the amount of valuable additional interchange generated beyond what could be possible in a conference room. I am confident that the panel members left Las Vegas with an understanding of the volcanic hazard issues for the waste repository that far exceeded what could have been generated through any number of hours of briefing in an office setting. Conversely, the CNWRA staff hopefully gained some new insights into their interpretive issues, from the in-depth on-the-outcrop discussions with panel members of broad experience and diverse backgrounds. At the very least, some intriguing new hypotheses were generated for testing by additional work, and some currently accepted interpretations were subjected to critical evaluation.

In the panel's field evaluations, we were guided mainly by our own experience with processes of basaltic volcanism, the superb natural and excavated exposures in the arid Yucca Mountain region, and the published observations and interpretations of these rocks by scientists from DOE, academia, and the USGS. For this last component, the CNWRA staff conscientiously tried to provide balanced summaries of alternate observations and interpretations by other workers, without unduly inserting their personal hypotheses or concerns, thereby leaving the panel members free to develop their own evaluations and interpretations. In hindsight, it was perhaps unfortunate that we were not accompanied by some of the volcanologists who have done the primary volcanic studies in the Crater Flat area. Nevertheless, doubts raised concerning several volcanologic interpretations of the Crater Flat cinder cones, based on broad experience of panel members with processes of basaltic volcanism, as detailed below, involve core issues for developing probability models of eruption recurrence and hazard evaluation that will have to be dealt with thoroughly before a permitting/licencing process can have scientific credibility. Further discussion of these critical issues in a field-workshop setting, bringing together the principal researchers with a broad spectrum of knowledgeable volcanologists, would seem the obvious next needed step. To the best of my knowledge, such a field-based review of existing data and interpretation, has not occurred previously, and the wealth of ideas that emerged from the brief examination by our panel indicates the power of such an evaluation approach.

Based on my brief time at Lathrop Wells and the older basalt cinder cones in Crater Flat, I have major questions concerning the fundamental physical-volcanologic interpretation presented in publications by the Los Alamos, USGS, and other DOE-sponsored research groups. In particular, the interpretation of polycyclic volcanism at Lathrop Wells and at North and South Cones was unconvincing, based my ability to locate and interpret relations between vents and lava flows as depicted on the published maps. The features I observed, as detailed below, seemed consistent with morphologically complex monogenetic eruptive activity. I would want to withhold any firm conclusions, however, until having an opportunity to study the three vent areas in greater detail, and in the company of volcanologists who did the mapping. Accordingly, the brief notes that follow must be regarded as fragmentary and preliminary.

Lathrop Wells cone

The Lathrop Wells cone is morphologically degraded despite the absence of well developed rills on outer slopes: the inner walls of the crater are anomalously low-angle, and all characteristic eruption-related structures, such as inward slumps and concentric fractures have been obscured by mass wasting. I doubt that exposure ages on any preserved material could reflect a true eruption age. The cone slopes are permeated by voluminous wind-blow sand; perhaps rill erosion has been impeded by the intense eolian processes.

No features that I observed convincingly indicate an eruption duration of longer than months to a small number of years. Two critical features of the published interpretations involving physical volcanology are especially troubling: (1) interpretation of the main cinder cone as younger than any of the flow lobes, and (2) interpretation of clusters of scoria mounds adjacent to the main cone as multiple vents for successive flow lobes erupted at substantial time intervals.

Late scoria from the main cone was deposited on still-hot lavas on most sides of the cone, as indicated by oxidation of scoria deposits everywhere they overlie the flows; one eastern flow lobe entirely lacks a scoria blanket, indicating emplacement of this lobe after cessation of explosive activity at the main cone. These features require that growth of the main cone have occurred concurrently with emplacement of successive flow lobes, rather than later. Further, I know of no historical analogue for a major cinder cone growing largely or entirely after emplacement of adjacent lava flows. The published compositional variability among flow lobes, and between flow lobes and cinder-cone ejecta, is small and seems well within compositional ranges documented during the course of individual historical eruptions, due to combined effects of crystal fractionation, magma mixing, and crustal assimilation.

Multiple low scoria mounds, which have been mapped and interpreted as vents for different sequential lava flows, appear to me most plausibly interpreted as disrupted masses rafted from the main cone by lava welling out from the cone base during draining of lava ponded in the main crater. The mounds lack central craters or agglutinate, occur on successive flow lobes as shown on published detailed maps, tend to be alined in arcuate belts along broad festoons of flow surfaces rather than along linear fracture-controlled trends, and are present near distal margins of some flow lobes. None of these features are consistent with a vent origin, or with eruptive geometries for any historical basaltic activity. However, disruption of scoria/spatter vents and rafting of vent fragments have been observed repeatedly during historic Hawaiian eruptions.

The paleomagnetic data reportedly showing coherent pole positions for scoria mounds and underlying flows deserve careful review, and comparison with data for analogous flow features: (1) what are the magnetic blocking temperatures for the oxidized scoria in comparison with temperatures expected in interiors of active cinder-cone vent systems, and how much angular rotation would be expected from a rafting emplacement process that largely involves concentric outward and upward inflation of a sluggish flow lobe? The reported 5^{o} difference in mean paleopole orientation between two flow packages, interpreted as indicative of a minimum 100-yr pause in eruptions, should be evaluated carefully for validity in terms of alternate possible age groups of flow units.

In my opinion, an urgent need is expert review of the currently controversial eruption and emplacement features displayed at Lathrop Wells by a small group broadly experienced widely respected volcanologists. The only productive format for such a review would be a field workshop guided by the geologists who have done the most recent mapping and volcanic-process interpretations. Certainly, the data published thus far provide an inadequate basis to evaluate alternative interpretations of the physical volcanology of the Crater Flat Cones.

Detailed physical-volcanologic studies by the CNWRA volcanology team could generate significant progress toward clearing up some of the uncertainties outlined above, but have some concern whether this is an appropriate role for CNWRA or NRC scientists at this stage of the repository evaluation process. Better quantitative data on sizes, densities, and vesiculation type of tephra at Lathrop Wells, especially for the flat-lying tephra blanket adjacent to the main cone that can be easily excavated by shovel, would provide additional critical data on eruption mechanics. It was not clear to any of us whether such data have been obtained by the DOE team during trenching that has subsequently been filled in.

Considerable emphasis has been given to the relative abundance of lithics in the Lathrop Wells cone, and possible implications for the amount of material that would reach the surface if the repository were volcanically disrupted. This site provide a marvelous sequence of natural drill cuttings that could provide detailed insights through the shallow subsurface if studied in detail. Some publications interpret the lithic fragments as consisting overwhelmingly of Tiva Canyon Tuff, yet no densely welded rhyolitic tuff, either Tiva Canyon or Topopah Springs Tuffs were evident to me. Sparse small clasts of partly welded crystal-poor tuff could be derived from high in the Tiva Canyon, but the Topopah nearby is seemingly entirely absent. The largest clasts were crystal-rich volcanic sandstone (local postvolcanic alluvium?) and a crystal-rich nonwelded ash-flow tuff (Rainier Mesa?). The overall impression is overwhelming derivation of the lithics from shallow depth. Additional work characterizing the range and proportions of lithic types, in conjunction with carefully drawn cross-sections across the local valley occupied by the basalt, would be informative. A shallow drillhole to definitive bedrock could provide rigorous constraints on thickness and lithology of the alluvial fill at modest cost.

Little Cone

The tephra at Little Cone differed only slightly from Lathrop Wells: the degree of vesicularity seemed more uniform, the deposits distinctly better bedded perhaps as a result of a more pulsating eruption, and the scoria clasts perhaps somewhat denser in overall average. Both cones appear to be dominantly Strombolian-type in eruptive style. The lava flow from Little Cone is so heavily mantled by alluvium that its original terminations are obscured; some surface magnetic profiles could help refine area and volume estimates.

Red Cone

The tephra deposits we examined at Red Cone (S side only) were notably different from both Lathrop Wells and Little Cone in their limited vesicularity and greater density; these angular dense fragments may record Vulcanian-type eruption of near-solidus to subsolidus ejecta during late stages of cone growth. Sintering of these tephra high on the eroded cone remnant may largely result from intense upward percolation of steam, driven by proximity to perched lava within the crater. The crater remnant is filled by weakly agglutinated dense spatter, plausibly interpreted as the most proximal fallback resulting from explosive disruption of the lava lake.

The flow lobes from Red Cone seem even more viscous than those erupted at Lathrop Wells, and are marked by striking lobate pressure ridges and ramp structures (shown, incorrectly on some maps as dikes, with notably misleading implications for vent geometry!). Numerous rafted masses of tephra, alined concordantly with flow margins just as at Lathrop Wells, have also been interpreted by others as defining abundant satellitic vents, and leading to interpretation of a much more complex vent system than seems merited by anything observed during our brief visit.

Only a few clasts of volcaniclastic sediment were noted, near the summit of the eroded main cone, but the sparseness of lithic clasts in comparison with Lathrop Wells may be more a function of depth to bedrock rhyolitic volcanics than great contrast in eruptive mechanisms. The alluvial fill beneath Red Cone, out in the center of Crater Flat must be much thicker than at Lathrop Wells, and the surface alluvium at least consists dominantly of sand and small pebbles, again pointing to a relatively shallow source for the lithic fragments at Lathrop Wells.

Pliocene vents

The complex dike swarm we examined led to much discussion as to whether multiple discrete eruptions were recorded, or alternatively near-surface en-echelon and otherwise complex fracturing in a shallow environment during a single eruptive episode, perhaps with only a few (or even a single) master dikes at depths of a few hundred meters. Detailed paleomagnetic data on the dikes could probably resolve these alternatives (I believe D. Champion has some data). Dike-wall structures I examined consistently indicated dominant upward flow, rather than lateral movement.

Fortification Hill:

The dikes at the south end of Fortification Hill provide a valuable probable analog for intrusive processes that should have occurred beneath Crater Flat basaltic cones and that need to be modelled for any scenario involving intrusive disruption of a repository. Most of the dikes are thin, 0.5 m or less, and thermal effects on brecciated Tertiary intrusive wall rocks seem megascopically modest, even where brecciated by faulting. Additional constraints on thermal history and fluid-rock interactions could be obtained by fission-track (apatite) and oxygen-isotope studies.

A key question is whether each dike represents a separate intrusive/eruptive event, or whether they collectively reflect complex near-surface fracturing and intrusion during a single or small number of volcanic episodes. Petrologic and paleomagnetic comparisons among dikes and with the Fort Hill lavas could be informative.

MAJOR RECOMMENDATIONS

Increase studies of basaltic volcanism in the Yucca Mountain region, including Miocene basaltic activity associated with waning of the ash-flow caldera complex.

Evaluate available granulometric data (e.g., scoria size, density, vesicle types) on basaltic tephra associated with Pliocene and more recent volcanism in the Yucca Mountain region, generating additional data where needed, and making comparisons with most suitable historical analog eruptions to constrain probable eruptive intensity of any future activity in the vicinity of the repository.

Prioritize project goals, focusing more effort on most urgent priorities. Reduce project load of administrative reports and technical reviews, generating additional time to complete in-depth studies in Yucca Mountain region and analogs elsewhere that can be written for publication in peer-reviewed journals that reach a wide scientific audience.

Augment interactions with tectonics and hydrologic study groups at CNWRA, LANL, and USGS.

Encourage organization of an invitational field workshop focused on physical volcanology, bringing together DOE, USGS, and Nevada project scientists with and uninvolved volcanology experts, to evaluate existing conflicting hypotheses on volcanic processes at Lathrop Wells and Crater Flat.

Review of meeting on Yucca Mountain Repository.

by Dr. A.R. McBirney, 31 October 1994

Introduction

The combined meeting and field trips during the week of 3-7 October were exceptionally well organized and effective. They provided a clear picture of the project and the problems involved in the assessment of volcanic hazards. I was impressed with the thoroughness of the studies completed by the Center for Nuclear Waste Regulatory Analyses and concluded that their approach has been logical and efficient.

In accordance with the plan laid out for our panel, my detailed comments are directed mainly toward the probability analysis, but they necessarily touch on volcanological aspects of the problem as well. In addition to material presented verbally, I have drawn mainly on the reports listed under References at the end of this report.

Methods

The available record of volcanism has been compiled in a geographic database[5] that includes all relevant information on the locations, ages, structural setting, and compositions of each known event. This information has been carefully analyzed and subjected to a variety of statistical tests to eliminate any possible bias[1-3,7] and to determine the distribution of events in time and space. The events have been divided into two sets, one Quaternary and the other Neogene. This division is a logical one in view of the relationship of pre-Quaternary eruptions to structural and igneous features that are probably no longer active. By using different combinations of possible ages, it has been shown[4] that, regardless of the period included, the events cannot be assumed to have a Poisson distribution in time and that it is impossible to judge whether volcanism has been waxing or waning during the last 1.6 million years. It has also been shown that the spatial distribution of vents is not random but is structurally controlled. Probability calculations have therefore assumed that the distribution of events in time and space is not random.

Recurrence rates are calculated using a Weibull-Poisson technique. While this is probably the best method for dealing with non-random volcanic events, the results are strongly dependent on the total time interval considered and the spacing of events within that period. When various combinations of these parameters were tested for the Yucca Mountain data, the predicted recurrence rates ranged from 1.5 to 11.5 volcanoes per million years. These rates were then used to obtain a spatial distribution of probabilities using a near-neighbor nonhomogeneous Poisson model. Results have been presented in a series of contoured maps of the Yucca Mountain Region showing the distribution of probabilities for various time intervals, recurrence rates, and number of near-neighbors.[3]

Finally, the uncertainties of these calculations have been evaluated[8] by testing how accurately they predict the distribution of events in a number of volcanic fields, including those for which the data base is much better than it is for the Yucca Mountain Region.

Limitations of the data

Inevitably, the analysis suffers from the limitations inherent in the geological conditions and the available factual information. One of the most critical elements in the probability estimates is the set of ages assigned to events. With only 8 documented events, the data base is only marginally adequate. As has been shown, changing a single event can result in large differences in the calculated probabilities.

The data base is not only small but imprecise. It includes age determinations carried out in different laboratories over a period of more than a decade. When the quality of these ages was examined and estimates were placed on the effects of uncertainties on the probability models, it was concluded that even when inaccurate and imprecise data are rejected, the ages currently available are inadequate for reliable probability estimates[7].

Recommendations

In view of these conditions, future investigations should be directed toward remedying deficiencies in the data and arriving at better probability estimates. This entails three main tasks:

(1) increasing and improving the data base,

(2) improving the geological evaluation of each event, and

(3) making the maximum use of tectonic and structural evidence to refine the analysis.

(1) Increasing and improving the data base.

A regional magnetic survey has identified at least five possible igneous features under the alluvial plain of Amargosa Valley. Only one of these has been confirmed by drilling and radiometric age determinations; it is essential that the others be tested as well. It is not enough to assume that all the anomalies are igneous and have the same age as the one that was dated. They could very well be younger or older. The magnetic polarity does not permit a distinction. Drilling is said to entail some sort of administrative difficulty, but if these localities are not properly examined, a reviewer of the project could logically argue that unfavorable information has been excluded from the risk analysis.

Since it has been concluded that the quality of the age determinations is inadequate for proper probability estimates, it would seem that the logical remedy would be to discard all previous work and obtain a complete set of age new determinations by a single laboratory using the best methods currently available.

(2) Geological evaluation of events

Geological judgment can be used to assign a relative importance to individual events and thereby improve the quality of probabilistic calculations. This is especially important in a case such as this where the data are limited. For example, field studies have shown that the basalts of Buckboard Mesa are more closely related to a caldera than to the fault system that seems to have controlled the other eruptive events. Moreover, the basalts are said to be petrologically distinct from those of Crater Flat and Sleeping Buttes. Simple geologic reasoning shows that including the Buckboard Mesa eruption in the analysis distorts the probability contours and obscures the structural control of vents related to the north-trending right-lateral fault system. While it is important to include all volcanic events, a reduced importance can be given to this particular eruption by including a factor that reduces its influence.

The interpretation of the Lathrop Wells complex is probably the single most important factor in a risk analysis. If the cone and associated lavas are treated as products of a series of eruptions widely spaced in time, the probability of a disruptive event at the repository site is greatly reduced from what it would be it they are taken as a single multi-phase event. Our field examination, brief as it was, convinced us that nothing in the geological evidence or radiometric dating conflicted with the latter interpretation. In reading the discussions reported in the record of the meeting held at the Alexis Park Hotel in 1992, I noted that the panel shared our skepticism of the "polycyclic" model. If this interpretation were presented at a public review it could easily be challenged by competent volcanologists.

(3) Tectonic relations

The studies thus far have shown that volcanism cannot be realistically assessed in an abstract statistical analysis; it must be linked to it tectonic setting. The Quaternary volcanism seems to be controlled by a north-trending, right-lateral fault zone independent of the earlier calderas. The vents are probably located on dilational fractures oblique to the main trend. This is seen most clearly in the Crater Flat complex. If this interpretation is correct, the probability model should take it into account and allow for the fact that future vents are more likely to fall within this main north-south zone than in the regions to the east or west. Instead of using a circle in the near-neighbor analysis, an ellipse elongated parallel to the faulting would be more appropriate.

Other cinder-cone fields can be used to develop a probability model based on this principal, provided the structural controls are analogous. The Springerville Field is the largest and best documented filed, but it differs in several ways from the Yucca Mountain Region.[9] Clusters of vents show only weak structural control and migrate in a seemingly random pattern with time. This is in contrast with other regions, such as the Snake River Plain, Iceland, or Southeastern Guatemala where the cones are closely related to linear structural features.

Conclusions

a. Because the data base is so small, it is important to ensure that all the events are fully documented. The nature of all magnetic anomalies in the Amargosa Flat area should be investigated by drilling and ages should be obtained on all of the igneous rocks responsible for these features.

b. The reliability of age determinations in the present data base differs widely. A completely new, uniform set of age determinations should be obtained from a single laboratory using the best modern techniques.

c. The methods used to estimate probabilities of a disruptive event at Yucca Mountain are sound. The technique of contouring the variations of probabilities as a function of distance distribution is conceptually effective, but it could be improved by making greater allowance for geological factors. Vents related to the earlier calderas should be given much less weight than younger ones associated with regional faulting. While, in principal, the validity of the estimate should be greater for the larger data set, the pre-Quaternary events have doubtful relevance to the present condition.

d. The structural setting that has controlled the location of Quaternary vents should be taken into account in assessing the spatial distribution of probabilities. This could be done by using an elliptical area rather than a circle for the near-neighbor analysis.

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CNWRA VOLCANISM RESEARCH PROGRAM PEER REVIEW PANEL, OCTOBER 3-7, 1994.

REPORT BY PANEL MEMBER STEPHEN SELF, OCTOBER 26, 1994.

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Introduction

I sincerely thank the scientists of the SwRI-CNWRA Volcanism Research group, C. Conner, B. Hill, D. Ferrill, and G. Stirewalt, their manager L. McKague, and NRC personnel, for an excellently organized, informative, and educational experience during the panel meeting. I am sure that I speak for all my fellow panel members in saying that we received all the information and help that we could have wished for. I felt that there were no gaps in the knowledge that it was appropriate for the CNWRA group to impart to us, that all sides of the issues involving young mafic volcanism in the Yucca Mountain region were fairly represented, and that our discussions were frank and open. NRC and CNWRA are fortunate to have such talented and dedicated young researchers pursuing the problems of recent volcanism in the vicinity of the proposed nuclear waste repository.

In two days in the office we were informed about the two main programs being undertaken by CNWRA, and in three field days we covered several of the young eruption sites in the vicinity of Yucca Mountain and an older, analog dike-fault interaction site near Lake Mead/Boulder Dam. During the office and field portions of the review I took notes, and it is largely upon these that my report is based. The only area where I felt deficient in necessary experience was in evaluating some of the newer geochronological techniques applied to the Crater Flat volcanoes by DOE workers. I realize that geochronology is not strictly within the purview of material that this review panel is evaluating, and that age-dating is not a part of the CNWRA volcanology program, but, nevertheless, it is important to the overall story at the Yucca Mountain region.

My previous involvement in the volcanology of the Yucca Mountain area was as a second author of a paper published in 1983 by Crowe et al. which reported field research done by Bruce Crowe, my then graduate student Robert Amos, and other colleagues in the early 1980's, and described the proximity of these young volcanoes to the Yucca Mountain site. In this paper we discussed the Lathrop Wells and other Crater Flat cones but I had not visited these volcanoes prior to this present 1994 panel meeting. My input to the study was to compare the data on the Crater Flat cones with those from similar volcanoes elsewhere, and to provide general information on Strombolian volcanism. It is fair to say that prevailing thoughts at that time, in my mind at least, were that the Crater Flat centers were monogenetic volcanoes, some perhaps possessing more than one vent, but with all activity at each volcano occurring within a short period of time. The concept of "polycyclic" activity at these volcanoes was not, to my knowledge, known or considered at the time that the work was done.

Scope of this report

I will evaluate, and make suggestions on, the two CNWRA research programs identified, namely, Field Volcanism (FV) and Volcanic Systems of the Basin and Range (VSBR). My particular topic of interest, as chosen by agreement between panel members, is *eruption mechansims*, and therefore most of my comments will be directed towards this part of the CNWRA programs. Therefore much what follows will pertain more to the FV part of the program than VSBR. I have also tried to keep in mind that much of the data output from the CNWRA programs will be used as input into a sophisticated set of models for testing the overall performance of the Yucca Mountain Waste Repository, referred to during the review as Performance Assessment (PA). For brevity, assessment of what I read prior to, or learned during, the review will be interspersed with comments and recommendations for future work. As much of the ensuing report concerns the young basaltic centers of the Crater Flat-Yucca Mountain regions, I will first give a brief synopsis and personal evaluation of the sites shown to us during the three field days.

Field sites visited

Lathrop Wells: The scoria cone and small stubby lava flows of this volcanic center are typical of the results of a normal Strombolian eruption proceeding with a fairly low magma flux. Evidence for an opening base-surge-producing phase was not convincing. The bed forms, fine grain size, and incorporation of silica sand in the dipping sequence of layers examined can be better ascribed to an eolian origin. Explosive interaction of magma with groundwater is therefore not absolutely demonstrated at this site. Parts of the cone appear to have been rafted away on lava flows several times during the eruption, causing the mounds on the north side, some of which are mantled by late-erupted scoria fall. Reddening of the scoria fall where it overlies the lava flows suggests that the flows were hot during much of the fallout. All of the features seen at Lathrop Wells are, in my experience, thoroughly typical of Strombolian monogenetic eruptions, and could be accommodated within a single eruption of some weeks to months duration.

Little Cones: The more SW cone was examined, it being a small, coarse-grained scoria cone composed of broken bombs transported downslope by grain flow. The eruption appears to have been pulsatory and the magma appears to have had sufficient volatiles to cause significant vesiculation of the pyroclasts. It would be worth examining the surrounding area for scoria-fall remnants to better determine the degree of explosivity during the eruption. The big, ropy-surfaced bombs, almost all of which shattered on impact, remind me of the products of the 1986 eruption of Izu-Oshima, Japan (Volc. Soc. Japan, 1988), which featured variable, sometimes very high fire fountains.

Red Cone: The predominance of dense, broken clasts in beds produced by grain flow down cone slopes shows that this cone formed from low fountains of poorly expanded magma. Sintering of the deposits suggests either a high accumulation rate or some post-depositional process. Gas-induced melting of parts of the cone, giving rise to dike-like bodies, plus the obvious redness, indicate that the whole structure was fluxed with gas and/or cooled slowly. Remnants of a small agglutinate pile or lava lake in the vent exist at the top of the cone. The associated lava contains marked ramp structures that cause ridges (ogives) across the slightly eroded top of the flow. These are not to be mistaken as dikes or vents.

Pliocene Crater Flat volcanoes: These stumps of basaltic fissure cones probably provide valuable evidence of the immediately subjacent parts of older Crater Flat-like cones. One or two thick dikes up to 4m across, both composite, were seen in the 1 km-long section examined. Evidence of magma movement, as preserved in the dike, appeared to support largely vertical transport. It could not be judged whether these were parts of one diking event/eruption, arranged en echelon, or two adjacent dikes of different ages, but such relationships should be resolvable by careful work. Control on the position of the paleosurface was seen by a dike-flow transition.

Fortification Hill: Dike-fault interaction stratigraphically beneath a basaltic center near Boulder Dam/Lake Mead show how faults can "capture" dikes. After the main group left, we continued to see some spectacular outcrops of the same dike (dike swarm) that showed unequivocal evidence of lateral movement of magma up the dike, en echelon structures, and composite formation (vesicle banding).

Field Volcanism (FV)

The documents and panel presentations on Field Volcanism research being undertaken by CNWRA staff constitute a very solid, well-founded piece of work. The research described will result, in the most part, to the desired understanding of the young basaltic volcanic system at Yucca Mountain. In detail, though, there are some aspects which could be fine tuned and I describe these below. The fact that some aspects of the study are not mentioned here indicates that I generally agree with their inclusion, methodology, and execution.

Overall direction of study

I would recommend that CNWRA scientists be more involved in direct active research on the young basaltic volcanism of the Yucca Mountain region (YMR), particularly in the comparison of the cones and flows there with analog sites elsewhere. This includes physical volcanology, basic geology (see later comments on drilling), and geochronology. Only by amassing an independent data base will the research results of other groups be properly evaluated.

Natural analog studies

Considerable effort has been put into these and they are an essential ingredient to the overall goal of the program. However, due in part to the shortcomings of work by other groups, I feel that the choices of analog sites were not the most appropriate, although they may have appeared to be with the published information at hand. It is my opinion that the volcanoes, eruptive style, and eruptive mechansims of the YMR have been poorly characterized by the other groups, despite over ten years of concentrated study. While research at Cerro Negro and Paricutin will be generally very useful, these volcanoes have eruptions of quite viscous, higher-yield-strength magmas than those occurring in the YMR, and have different styles, characterized as violent Strombolian or Vulcanian (see Walker, 1973). Parts of the Tolbachik eruption make a better analog, and Heimaey, Iceland, 1973 (for example, see Self et al., 1974, for an earlier study), may be an even better one. Heimaey provides a well-studied example of a Strombolian monogenetic volcanic eruption and its products, possessing many of the features that this reviewer saw at Lathrop Wells. Records of drilling conducted in the years after the eruption should also provide a history of the thermal regime around the site.

Research into phreatomagmatic analogs on the grounds that Lathrop Wells volcano had an opening hydromagmatic phase is probably not warranted, as the deposits in question are probably eolian (sand-dunes). However, in the big-picture of possible volcanism in the YMR, phreatomagmatic volcanism should not be overlooked, especially in the long-term (> 1000s years) when repository performance in future climatic regimes needs to be evaluated.

In the study of analog volcanoes, physical volcanologic studies (granulometry, particle component analysis, etc.) is desirable on samples collected because it provides a quantitative data base on which to compare samples for the basaltic volcanoes of the YMR. The end result will be much more amenable to inclusion in the PA models which will ultimately be constructed. They will also provide a basis for modeling eruption dynamics, using the methods recently described by the Walker-Sparks-Woods-Bursik school, enabling clast dispersal patterns to be modeled rigorously, for instance. This reviewer is happy to provide appropriate references on these particular matters to the CNWRA group.

Basaltic volcanoes of the Yucca Mountain region (YMR)

More effort should be made to characterize the eruptive styles and mechansims of these volcanoes. The cones and their associated fall deposits are just about well-enough preserved to enable collection of grain size data and samples that will permit a more rigorous estimate and comparison of eruptive style. An all-out search for preserved ash deposits in the region is warranted. Reworking of pyroclasts after deposition by wind and water should also be considered, and evidence for or against should be sought.

The volumes erupted should be estimated using a standard procedure, perhaps that of Pyle (1989) and Fierstein and Nathanson (1992), which will allow information collected from the YMR scoria cones and fall deposits and from analog studies to be compared on an equal basis. The advantage of the above method is that it requires very few points (isopachs), and so may be useful for the eroded YMR basaltic volcanoes. Volumes erupted can be used as a constraint on suitable analog volcanoes and to evaluate monogenetic vs. polygenetic (polycyclic) origin for the YMR basaltic centers. Small volumes per center would seem to argue against polycyclicity on the grounds of thermal inefficiency. Part of this would also involve estimates of intrusive volumes beneath the cones.

If thickness and grain size can be collected on the fall deposits from the cones, then the Pyle (1989) method of plotting b_c and b_t may be used to categorize the deposits. This scheme, a development of the F vs. D plot of Walker (1973), of which the CNWRA researchers are aware, has less dependency on assuming a thickness at vent and, once again, can be accomplished with a few (lucky?) data points, making it amenable to eroded deposits. Hard data will result from this approach, such as distances that clasts of various size (density) were dispersed from YMR basaltic eruptions. These would seem to be vital *area terms* that can be used in PA procedures.

It would also seem appropriate to take more action on the possible buried volcanic centers in Amargosa Valley and drill some holes to examine what they really are What is the age and composition? Are they part of the Crater Flat field or not? These issues are vital to the overall area considerations and to determining the number of eruptive events that have occurred in the region.

Eruption - intrusion scenarios

While eruption scenarios are being considered via analog studies, a result of the physical volcanological studies discussed in the previous section would be improved dynamic eruption models for the YMR basaltic centers. Intrusive processes are also being considered and a good analog would be some tank experiments in which "magma' was injected through a more viscous medium towards a surface and a buried void (a scaled proxy for the Yucca Mountain repository). If typical YMR basaltic magma batch volumes were known, these could be used to examine the possibilities of eruption vs. intrusion as a dike interacts with a buried system of repository chambers. Is intrusive interaction or explosive venting the bigger threat in the likelihood of a future eruption impacting the repository? Such questions, although perhaps highly exploratory, should be entertained.

Volumes of subjacent intrusive magma will also influence thermal models in the cooling-down stage after eruptive activity. The Tolbachik study is an important analog here as the slow cooling may well be an artifact of a larger volume of subjacent magma in that part of the bigger Tolbachik volcanic system?

Dikes

Current research into dike-fault interactions is well-founded, considering the overall tectonic setting of the Yucca Mountain region, and should be continued and expanded. Trends of dikes in the region, and controls thereon, need to be investigated more thoroughly. An aspect of this is whether .YMR basalt centers are fissure controlled or constitute a clustered cone field (a *monogenetic volcano field* is another term used)? C. Conner is well placed to head such research, having experience in the Springerville and central Mexican volcanic zone fields. Also are centers such as Red and Black Cones on one fissure that erupted only once? Such questions impact eruption probability studies in a large way, and will also be important to area terms in PA modeling.

Volcanic Systems of the Basin and Range (VSBR)

A valuable start has been made on documenting useful attributes of the other young basaltic volcanic center in the general region, but it appears to have been dominated so far by compilation of available literature and by a GIS. While this is useful, it should only be the start. Specific recommendations, made mainly by fellow panel members and onlookers at the review, that will improve the direction and results of the study are targeted briefly here. The order in which they are listed is of no significance.

1. Increase volcanological study of similar systems in the Basin and Range (Reville field, Lunar Crater, Craters of the Moon, etc.). Build up a data base for comparison with YMR basaltic centers.
2. Examine overall tectonic controls on mafic volcanism in the Yucca Mountain area.
3. Seriously reconsider the basis for selection of the whole suite of volcanoes that are considered part of the YMR young basaltic group, i.e., those for which a repeat event would be a direct possible consequence to the Yucca Mountain repository and which will be considered in probability analysis. Some of the 8-10 Ma age centers can be possibly be omitted and aspects such as he relationship of mafic centers to the Timber Mountain caldera cluster are important. The nature of the buried Amargosa Valley centers are also of direct concern. This also involves the next item to be mentioned.
4. Compile data on the composition (geochemistry) and magma properties of YMR basaltic volcanoes and of other similar centers in the Basin and Range. This will allow the classification of mafic centers into those with and without crustal contamination, which may provide a parameter used to constrain the number of centers considered (assuming that the Timber Mountain-related ones should have crustal contamination whereas mantle-derived magmas such as those at Crater Flat should not). It will also provide another database for comparing centers of similar magma properties on the basis of eruptive behavior.
5. Test whether mafic volcanism in the YMR area is waning, as seems to be common consensus in some circles. On what grounds is it waning: periodicity of eruptions, volume of events, explosivity? Little of the work to directly answer these questions has yet been done by any group involved in research in the region.

Other issues

Two other matters seem important to the overall issues of volcanism in the Yucca Mountain region and the future threat of igneous activity to a waste repository.

1. If the repository is to have a life-span of 10^4-10^5 years then future climates, probably cooler and wetter, must be considered. Of direct impact on volcanism is the possibility of phreatomagmatic activity. I would urge the CNWRA group to look further into the climate modeling done so far to predict rainfall and future water table levels at Yucca Mountain. Even if the water table may not rise to the level of the repository, any rise

will increase the chance of magma-water interaction, and perched water tables may come into existence. I am unsure of how much is known about modeling of future climates?

2. The whole problem of how to handle probability of eruption needs to be seriously reconsidered. Variance within each input into the controls on when and where an eruption will occur should be examined at each step before final probabilities are produced. I trust that other panel members will deal with this point in much more detail and in a more expert manner.

Summary

My overall impression of the program of work being undertaken by the CNWRA volcanology group is definitely positive, but there seems to be a lack of focus and this will soon start to impede pregress in essential area of knowledge. The opinions I have formed of some of the work that the CNWRA group must evaluate is not good, however, and the onus is on CNWRA to perform their task in the most geologically rigorous manner in order to build a solid, testable case. I urge the Volcanology Program to be more active in pursuing original research, although I realize that it has not necessarily been part of their mandate up to this time. I am concerned that the research which needs to be undertaken is very time consuming and that the personnel with whom we have had contact may not be able to achieve it all in the time available. More person-power and/or relieving the volcanologists of some of the tasks of internal report writing, which seems to have occupied a lot of time in the past two years, are obvious solutions.

Conclusions

More specific research goals, such as those listed below, should be pursued by the CNWRA Volcanology Program. These should mainly center around investigative volcanology and geochemistry on the basaltic volcanoes of the YMR group and associated centers. Performance Assessment goals are likely to be better met for the young basaltic volcanism in the Yucca Mountain area by a quantitative approach to study of the volcanic centers. This includes refining the number of past eruptive centers that pose significant volcanic risk to the waste repository site and hence the likely frequency of future eruptions, the number of vents active in one eruption and the duration of such an event, identification of the potential products of one eruption, and evaluation of the styles and mechanisms of surface and intrusive activity.

Intrusion vs. surface activity should be evaluated, particularly with respect to injection of magma into a buried repository, which could be investigated by experiments. Is there a favorable side to intrusion of magma into a waste repository?

Area terms are more likely to be satisfied by considering eruptive dispersal of particles, distribution of lava flows, and shapes and dimensions of subsurface parts of the volcanic system. This adds up to an increase in the amount of physical volcanology that should be applied to the YMR basaltic volcanoes.

Study of natural analogs is essential to this program but should not become an end to itself. The purpose of the analog studies should be to provide comparisons to the YMR volcanoes and other young basaltic volcanoes in the Basin and Range province.

Field observations such as the panel were able to make at the YMR basaltic volcanoes are inherently reliable only at a certain level. Detailed follow-up work is needed to prove or disprove ideas suggested by initial field assessments. Each piece of detailed analytical data bearing on the problem should be subjected to both scrutiny and testing to see if it fits logically into the evolving model for these volcanic centers. This approach apparently has not been adopted by other groups working on these volcanoes, and it is by application of this simple rule that the CNWRA scientists can substantially advance our understanding of the volcanic risk to the Yucca Mountain waste repository site.

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PEER REVIEW OF VOLCANISM RESEARCH BY NRC/CNWRA

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October 28, 1994. George P.L. Walker Oct 28, 1994

INTRODUCTION

A volcanic field, that of the Yucca Mountain region (YMR) consisting of several small and discrete basaltic volcanoes, occurs within 10 to 20 km south and west of Yucca Mountain. These volcanoes outcrop over 18.5 km^2 and are scattered over 200 km^2 of country. Their radiogenic ages span the last >4.5 Ma. The volcanic field is part of a larger field embracing Sleeping Butte and Buckboard Mesa and extending as far back as 8 Ma. The youngest volcano is that of Lathrop Wells, having a radiogenic age of probably <200 ka. The youthfulness of this volcano suggests that the volcanic field is still "alive" and is capable of having future eruptions.

The presence of this volcanic field so close to the candidate repository site for high level nuclear waste in Yucca Mountain gives rise to concern that the integrity of the site could be compromised if a future eruption took place in the YMR.

Fortunately, from the viewpoint of the site integrity, the number of basaltic volcanoes in the YMR is small and eruptions are very rare events. From the viewpoint of probability modeling (that volcanism in the YMR will recur within a given area and timescale) however, the number of samples (i.e. the number of volcanoes or alternatively the number of eruptive events that the volcanoes record) is also small. If it were to be established that any particular volcano is"polycyclic" (i.e polygenetic; constructed by two or more eruptive events) this would increase the sample size and change the probability, and similarly if it were to be shown that any specific pair of volcanoes was actually the product of one eruption so decreasing the sample size.

Following a 2-day conference in San Antonio on October 3–4 several volcanoes in the YMR were visited on October 5–7 1994. This fieldwork visit was the most valuable part of my visit. It gave me an excellent opportunity to form some kind of opinion regarding these matters and the kind of possible directions that future studies might usefully take in the YMR.

I thank personnel of the NRC and CNWRA, Chuck B. Conner and Britt E. Hill (Principal Investigators in Volcanism research) and their colleagues and co-workers, for their excellent presentations of the facts and issues raised by their volcanism research, and for the very instructive visits they organized to some of the YMR volcanoes.

In the following I summarize my observations on the volcano visits, and specify ways in which my interpretations conflict with published interpretations by other (non-NCR/CNWRA) workers. This is highly relevant to understanding the YMR volcanic field. I follow this with my peer-review, and finally suggest various directions for future volcanism research.

DESCRIPTION OF VOLCANOES VISITED

The Lathrop Wells Volcano.

The Lathrop Wells volcano consists of a cinder cone about 140 m high, a lava field covering about 3.5 km^2 on the east and south of the cone, and a scoria-fall blanket extending from the foot of the cone to (in outcrops that I visited) at least about 400 m away. The cone is well exposed by quarrying and is composed of coarse scoria of what appear to be normal-strombolian deposits. The scoria fragments are well vesiculated. Some spatter lumps occur, but I did not see any significant agglutination. Bombs are fairly abundant and are mostly <1 m in size. Most are weakly if at all vesicular, and are very dense.

The constituents of the cone have evidently been redistributed by grainflows. Evidence for grainflows is the occurrence of inverse-graded bedding units, and breakage of cinder clasts (on cooling joints that cut across vesicle zonations) and dispersal of the resulting cobbles. Grainflows very commonly occur on cinder cones oversteepened by massive deposition around the crater rim, and occur during growth of the cone.

The whole core of the cone is pervasively reddened, and the scoria fall blanket is reddened in its lower and middle parts where it rests on the lava flows. Empirical observations are that such reddening results from a kind of "baking" in parts of the deposit that stay hot longest.

The lava field east of the cone is diversified by mounds averaging roughly 100 m across mostly of red scoria. I interpret these mounds to be either a scoria-fall blanket disrupted because it was deposited on active lava flow, or portions of collapsed cinder-cone material that were carried laterally by flowage, rafted on the underlying basaltic lava. Scoria-fall rafts broken by movement of the underlying lava, and portions of cinder cone carried away on the surface of lava, are very common and good examples occur, for instance, in the 1955 and 1960 eruption products at Kapoho, on Kilauea volcano. I witnessed the processes happening on Heimaey (Iceland) in 1973.

Several rather short, stubby and rough-surfaced lava lobes occur around the foot of the main cone on its east and south sides. These lavas can be placed in a relative age succession according to the thickness of scoria-fall on them.

At a point roughly 400 m ENE of the cone there is a small and shallow valley containing sandy ash deposits. These deposits are well stratified, and the lateral impersistence of the beds is suggestive of dune bedding. A few beds have a bimodal particle population, and contain pieces of lightweight pumice up to about 1 cm in size associated with the submillimeter-sized sand. I suspect that hydraulic (strictly, pneumatic) equivalence exists of these two grain sizes. A variable proportion of the sand is silicic. The fact that the dip of the bedding is in the same southerly direction but is consistently steeper than the ground-surface slope suggests that this deposit is essentially the eroded remains of a large sand dune. Undoubted large and isolated sand dunes occur elsewhere near Lathrop Wells. If this deposit is a sand dune and the beds are on the lee side, deposition would have been from predominantly northerly winds. It does not appear to me likely, from what I saw, that this is a base-surge deposit, or that the fine sandy character is indicative of a phreatomagmatic eruption.

Little Cone.

Little Cone consists of two small cones lying on a NE–SW line, the south-western one being the larger. Probably both cones are smaller than originally: some erosional degradation has undoubtedly occurred, and some burial beneath alluvium may also have occurred. A pit reveals coarse scoria cobbles plus some bombs. I collected a sample from this pit for sieving.

Red Cone.

Red Cone rises about 120 m above its surroundings, but the original height was certainly greater and has been reduced by erosional degradation and partial burial beneath flows and alluvium. Two main types of pyroclastic deposits occur:

1) a well-lithified deposit composed of blocky and angular dense-scoria clasts, constituting the crater rim ; and

2) dense spatter and agglutinate, with associated bombs, veneering the inner slope of the crater.

The crater rim deposits are coarse and poorly vesicular dense scoria clasts and are crudely bedded. Dip is mostly outwardly-directed. Bedding is hard to find in some of the smaller (<2 m across) outcrops. I did not see any macroscopic deformation of the clasts, and I speculate that lithification was due either to partial fusion resulting from permeation of hot gases through the deposit, or by sintering of hot clasts under conditions of rapid accumulation. In one outcrop on the southwestern rim I saw what I interpreted to be a passage from scoria-fall into a dark aphanitic rock strongly suggestive of in situ fusion induced by hot gases in a fissure. Nearby I saw an irregular and sharply-bounded dike-like body <1 m thick of aphanitic rock such as would be consistent with flowage of material fused in situ into a fissure.

From what I saw, the clasts constituting Red Cone seemed to be of weakly vesicular scoria such as might result from eruption of magma considerably more viscous than that at Lathrop Wells volcano. I leave open the question of the extent to which fragmentation of this scoria to generate the present small cobbles took place by tossing and tumbling as repeated explosions probably of vulcanian type took place in the crater, or in grainflows on the crater sides. I do not recall seeing any clear example of grainflow bedforms or the inverse grading of clasts that results from the grainflow mechanism.

The Crater Flats volcanic center(s).

Eroded stumps of one or more basaltic volcanoes giving radiometric ages of about 4 Ma occur in Crater Flat. My visit to this site was too short to enable me to form an opinion of the number of events recorded there, except that I saw two dikes suggesting that at least two magmatic events had occurred.

The dikes are very shallow, indicated by the vesicularity of parts of both. Both dikes consist of zones having contrasted vesicularities and jointing habits, apparently not chilled against one another, suggesting that their formation was by close-spaced injected magma pulses. In the larger dike the distribution of these zones is strikingly asymmetric. In some zones the dikes have a close-spaced platy jointing parallel with the dike margins. In the vesicular zones the vesicles are locally strongly deformed by flow and the foliation (the plane of flattening) of the vesicles locally curves around "nodes" that appear to be places where magma flow was concentrated and was roughly vertical.

These dikes show many features of interest, and a thorough study of their field relationships is warranted.

GENERAL OBSERVATIONS

Conflicting interpretations.

According to some published accounts, Lathrop Wells volcano is "polycyclic" (i.e. polygenetic: built by two or more eruptions). This conclusion appears to depend on the interpretation of scoria mounds found around the foot of the main cone as small cones situated at multiple primary vents. According to this interpretation, rough alignments of these mounds would reflect primary eruptive fissures, three of which (in addition to the fissure presumed to underlie the main cone) would then be required to account for all of the mounds. Also, cinder cone and lava flows have been interpreted to form during separate eruptions.

I was privileged to watch (on Heimaey, Iceland, in 1975) scattered mounds similar to those of Lathrop Wells form by totally different mechanisms, namely the lateral carriage and breakup of a scoria-fall blanket on a lava flow, and rafting away of volcano-collapse debris (arising by partial collapse of the main cinder cone) on the surface of lava flows.

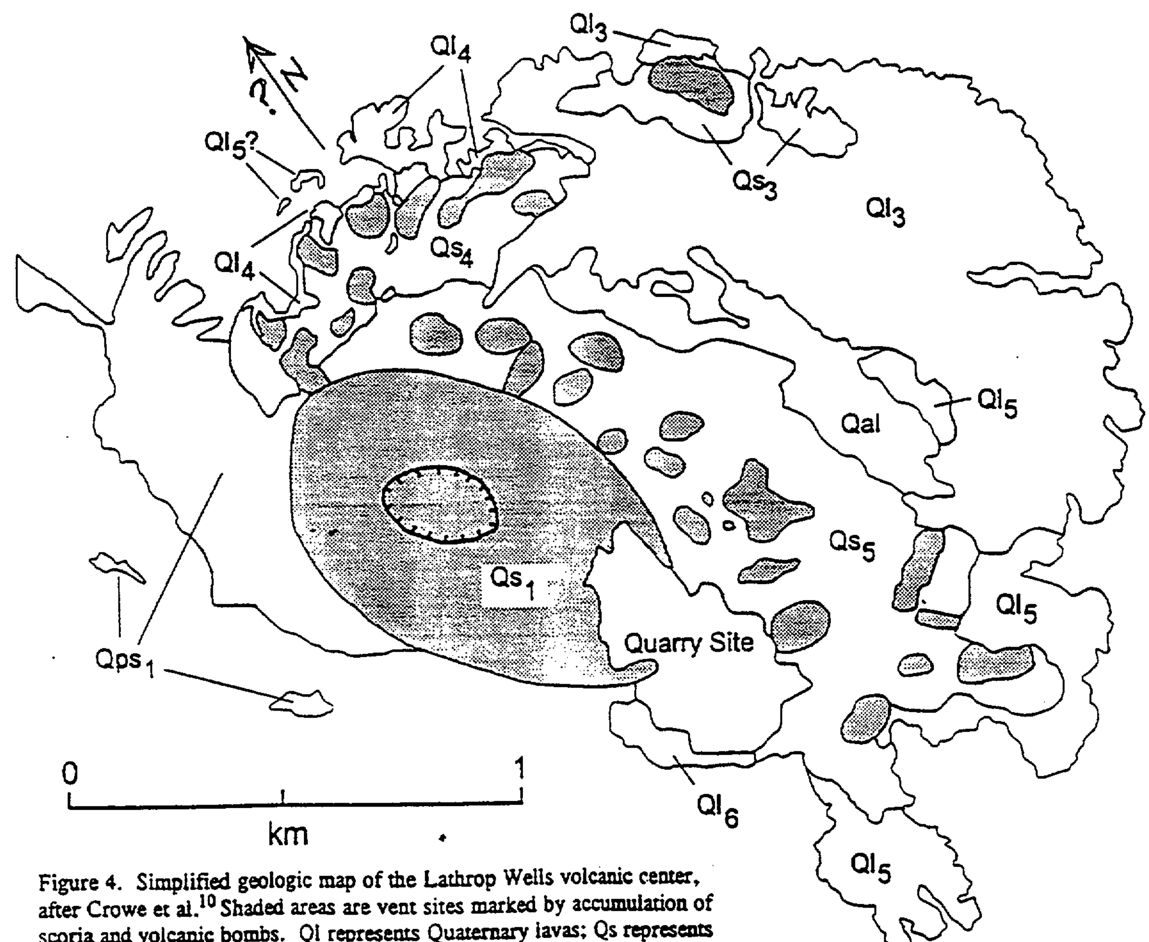


Figure 4. Simplified geologic map of the Lathrop Wells volcanic center, after Crowe et al.[10] Shaded areas are vent sites marked by accumulation of scoria and volcanic bombs. Ql represents Quaternary lavas; Qs represents Quaternary scoria deposits. Qps represents Quaternary pyroclastic surge deposits. Unit numbers increase with increasing age.

This published map of Lathrop Wells volcano shows numerous small stippled areas representing small scoria mounds outside of the main cone. I have seen an interpretation in which these mounds mark multiple vents developed on several fissures additional to the main vent. A much simpler interpretation is that the mounds are scoria rafts carried laterally on lava flows. I have watched such rafts forming. Ashy material at one of the small areas labelled Qps is interpreted as pyroclastic surge deposits. I was unimpressed by this interpretation.

At Red Cone also, I was puzzled by the multiplicity of "possible vent sites" shown on the published geologic map. Some of the "dikes" shown may have been confused with a steep platy flow structure (ramp structure) as is locally shown at the top of the aa lava flows.

I did not see any reason to doubt that Lathrop Wells is a monogenetic volcano of the type that, in observed examples, forms typically in days to months. The variable thickness of scoria-fall deposits on different lava lobes, and the red color of this scoria where it was deposited on hot lava, means that pyroclastic deposits of the main cone and scoria blanket deposits formed concurrently with lava effusion.

Also I do not think that the fine-bedded ashes found several hundred meters WNW of Lathrop Wells are either primary fall or surge deposits, or that the fine grainsize of these deposits indicates phreatomagmatic activity.

Excessive paperwork?

I formed a strong impression that the researchers are overburdened with paperwork, and spend a disproportionate amount of time writing reports not for publication. It would be far better if the time were used to write papers for publication in national or international scientific journals.

POSSIBLE DIRECTIONS FOR FUTURE RESEARCH

Study of eruption dynamics.

The traditional approach to the study of small and young basaltic volcanoes is geochemical. Geochemistry is a useful tool to aid in correlation of eruptive units, but it does not contribute much to determining the dynamics of basaltic eruptions. Eruptions involve physical processes, and can be best investigated by making physical measurements (for example, grainsize studies) on the pyroclastic products. The fact that such physical measurements have not been published for any of the hundreds of small basaltic volcanoes along the SW edge of the Basin and Range Province from Truckee/Donna Pass to the Cima Field suggests to me that little understanding exists of the dynamics of eruptions that produced these volcanoes. It is true that the arid climate of this part of Nevada and California is not conducive to the preservation of distal pyroclastic products, but careful searches might be productive. From what I saw of the Lathrop Wells volcano, the ash blanket deposit there is probably exposed adequately to permit a good reconstruction of the eruption dynamics. I strongly recommend that a study of eruption dynamics be undertaken among these Basin and Range volcanic fields.

Personnel of the NRC/CNWRA (C. B. Connor and B. E. Hill) recognized that the analogy approach, to improve understanding of the YMR volcanoes by studying recent analogs elsewhere, is potentially very powerful. In similar circumstances I would have followed this same approach myself. To this end they did field work on three volcanoes (Paricutin, Mexico; Cerro Negro, Nicaragua; and Tolbachik, Kamchatka). Their rationale is sound, and from published data their choice of these particular volcanoes is also sound. From unpublished data not available to them, I suspect that some of the three chosen volcanoes were the scene of violent-strombolian activity, and not normal-strombolian activity that characterizes Lathrop Wells and Little Cone. I suspect that the three volcanoes chosen as analogs may turn out to have higher crystal (phenocryst and microphenocryst) contents, and that magma rheology determined the more violent eruptive behavior. I strongly recommend that research should continue on the three analog volcanoes so as to document their eruption dynamics.

In violent-strombolian activity, the juvenile magma is highly fragmented, and volcanic ash predominates among the ejecta instead of the coarse cinders of normal-strombolian eruptions. Violent-strombolian eruption plumes tend to be higher, and ash particles (because of their lesser fall velocities) are carried to higher in the plume, and are more widely dispersed by the wind. A large proportion of the pyroclasts extend beyond the foot of the cone and contribute to areally extensive ash blanket deposits.

Good documentation, yet unpublished, exist on the deposits of violent-strombolian eruptions at three Mexican volcanoes, namely Paricutin (erupted 1943–52), El Jorullo (erupted 1759–74), and Xitle (prehistoric). Violent-strombolian activity may result when juvenile magma has a higher viscosity and yield strength than in normal-strombolian activity, so inhibiting the escape of gases and increasing the explosive violence.

Dikes.

The general NE or NNE strike of dikes, the elongation of Lathrop Wells cone, the alignment of Little Cone and its neighbor, the alignment of Red and Black Cones, and the general northerly strike of faults in the YMR, make it quite plausible that dikes may have followed the line of some faults and entered the Yucca Mountain block. I understand that many holes have been drilled in and near the block. These holes would be the obvious place to look for dikes. Geophysics, such as ground magnetic surveys, might offer the best means of locating concealed dikes provided that the dikes are sufficiently shallow. Geophysics might also resolve whether Red Cone and Black Cone lie on the same fissure or on separate fissures.

The anisotropy of magnetic susceptibility (AMS) technique will give the magma-flow direction in exposed dikes such as those of Crater Flats.

In the event that a dike from a future magmatic event did enter a repository on Yucca Mountain, it might form an intrusion in a repository vault. Depending on circumstance it might either carry away the waste storage canisters or solidify in situ between and around the canisters so enclosing them in a sheath of basalt. Clearly, dikes have been injected in the past in the YMR, and will likely be injected in the future. The hidden parts of dikes may possibly extend laterally farther than the volcanoes and reach closer to the repository site.

Future silicic volcanism

I am slightly concerned by the tacit assumption that silicic volcanism has ceased in the YMR. The candidate Yucca Mountain repository site is situated near the edge of the Timber Mountain caldera complex from which a great volume (thousands of km^3) of ash-flow tuffs have come. The latest silicic volcanism in this region took place about 9.5 Ma, and there has been ample time since then for the silicic magma chamber(s) to have cooled and crystallized. With the continuation of basaltic volcanism (albeit on a very small scale) in the area it seems possible that silicic material may be reactivated. The proposed seismic tomography study might be the best approach to evaluating this possibility.

NOTES ON TUNNEL STABILITY

This is outside my expertise, but I feel I should note in regard to the long-term (10 ka) stability of tunnels excavated in ash-flow tuffs and in highly seismic areas, that a great number of ancient tunnels occur in Central Italy. Some were excavated as tombs by the ancient Etruscans about 2500 years ago. Wall paintings survive in some. Others (the Catacombs below Rome) were used by the early Christians about 1900 years ago. Also I understand that extensive labyrinths were excavated as residences in Cappadocia (Turkey) about 1500 years ago. My general impression is that tunnels in Central Italy have been remarkably stable, and a visit might be very revealing. Of course those ancient tunnels may be an order of magnitude narrower and lower than the chambers envisaged in a nuclear waste repository.

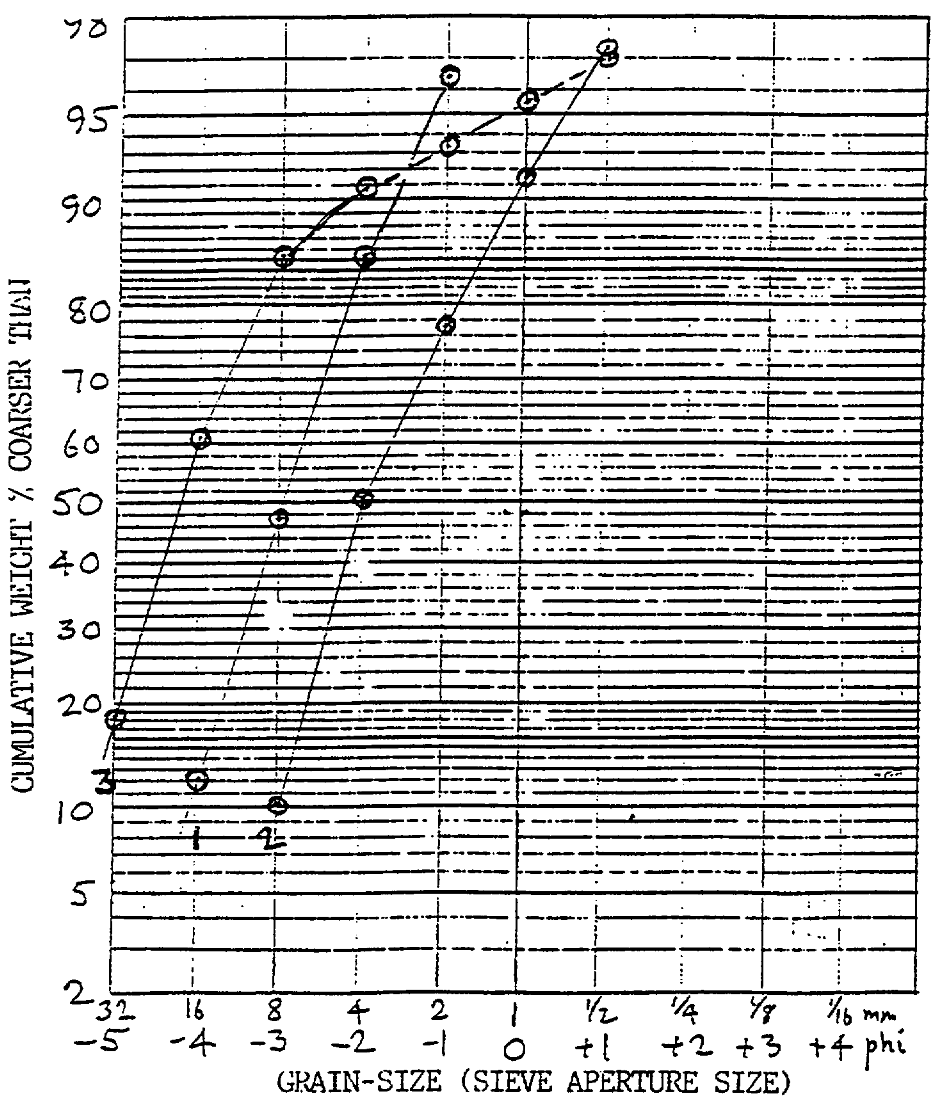
Summary.

The volcanism programs are well conceived and the personnel are energetic and enthusiastic people who are well capable of implementing the programs. These personnel have available a great number of small volcanoes in the southern part of the Basin and Range Province, extending from Donner Pass/Truckee to SE of Cima. If I were in their position I would range widely over this province selecting suitable examples for detailed study. I would concentrate on eruption dynamics since that is the aspect of these volcanoes about which least is known. I would regard the study of modern analogs as an essential and integral part of the task, and I would hope for a reduction in unnecessary report writing.

APPENDIX-GRAINSIZE ANALYSES

I collected samples from two outcrops of the Lathrop Wells volcano scoria-fall blanket. One sample (#1) came from a pit just off the SE foot of the main cinder cone, and the other (#2) came from a road cut about 400 m farther south. I collected one sample (#3) from Little Cone, from a pit on the western side of the main cone.

All three samples are well sorted (Inman graphic standard deviation 0.9 to 1.1 phi) and all are coarse (median grain diameters -2.0 to -4.2 phi) and compare very closely with examples of normal-strombolian eruptions elsewhere. Sample #2 has a maximum and median grainsize exactly half that of sample #1. A grainsize decay rate to half in a distance of 400 m is typical for normal-strombolian activity

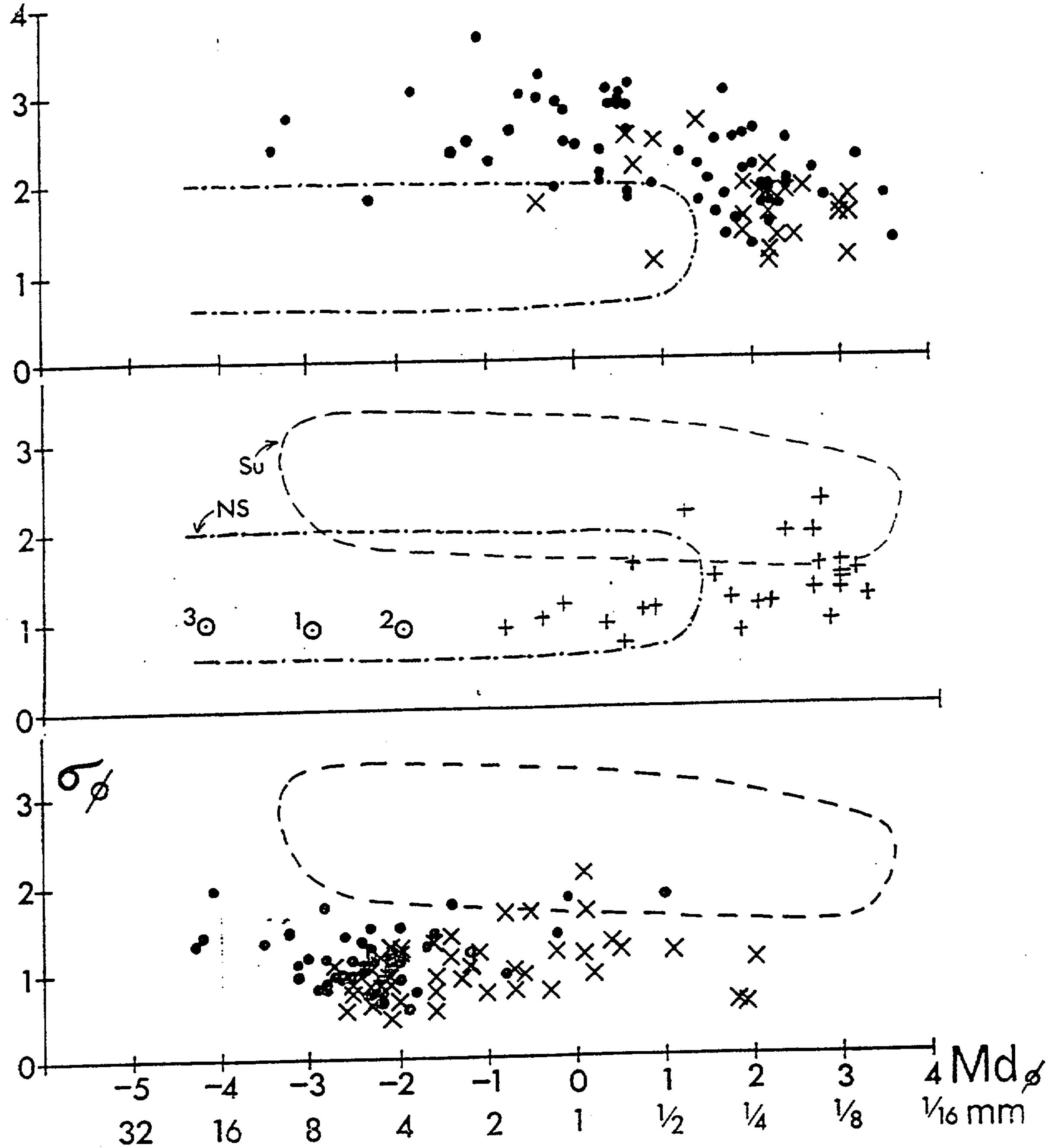


Cumulative probability plots, showing cumulative weight percentages of particles coarser than indicated sieve-aperture size, for three scoria samples from the YMR volcanic field:

#1 Pit just off foot of cone, Walthrop Wells Volcano
#2 Roadcut exposing scoria fall on lava flow, about 400 m south of cinder cone of Lathrop Wells Volcano
#3 Pit on western side of Little Cone volcano.

sample	median diameter (phi)	graphic standard deviation (phi)
#1	-3.0	0.9
#2	-2.0	0.9
#3	-4.2	1.0

(note: the fine "tail" of sample #3 consists partly of sand blown into the scoria deposit).



Plots of Inman parameters graphic standard deviation (sigma phi) against median grain diameter (Md phi), for surtseyan ashes (above) and normal-strombolian scoria-fall deposits (below), after Walker & Croasdale 1972 (Bull Volcanol., 35: 303-317). Dashed line outlines field of surtseyan ashes (Su). and dot-dashed line the field of normal-strombolian (NS). Dots represent samples collected from the cone, and crosses represent samples of blanket deposits outside the cone.

The middle diagram plots unpublished data from the violent-strombolian deposits of Paricutin. They are significantly finer than normal-strombolian, but better sorted than surtseyan.

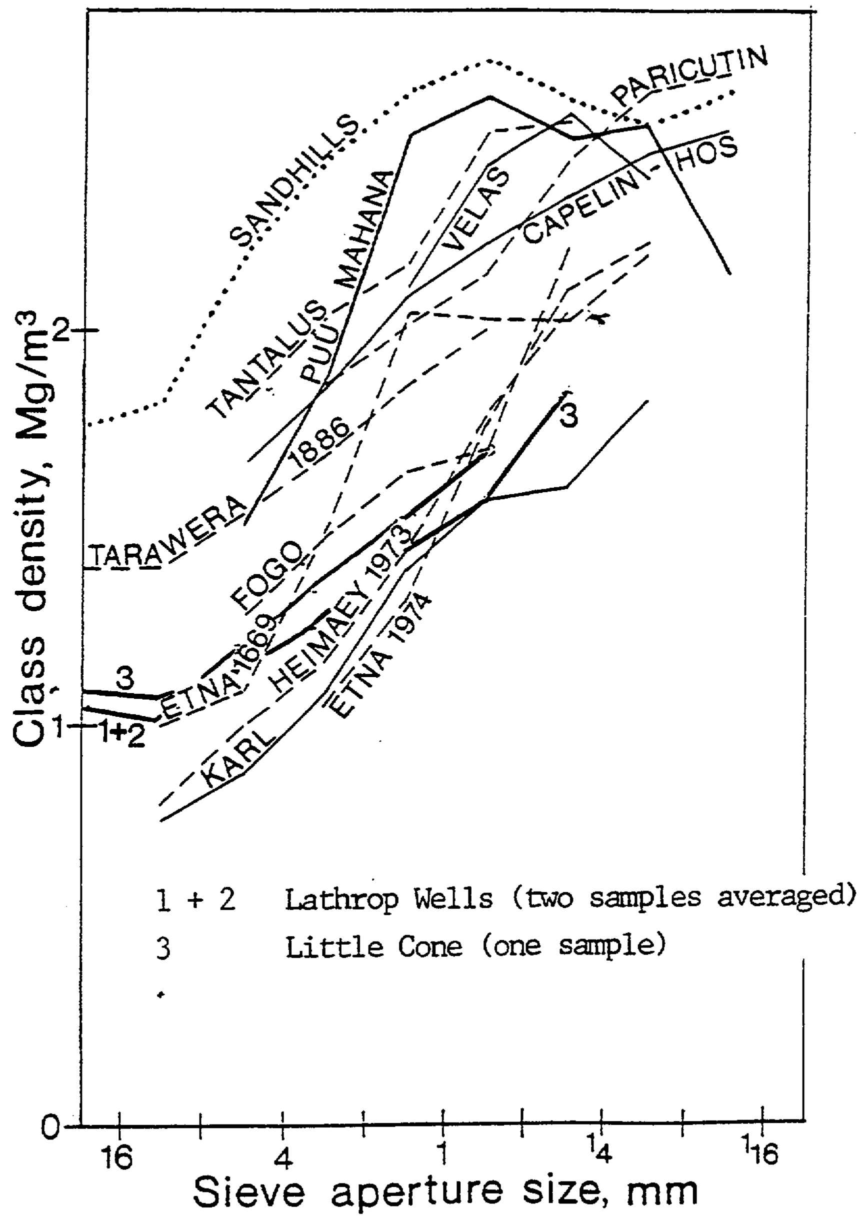
Dot-circles represent samples from Lathrop Wells blanket deposit (#1, #2) and Little Cone cone deposit (#3); all three are typically normal-strombolian.

Grain density.

When a sample of a pyroclastic deposit is sieved, the grain density of each sieve class can be determined from the mass and volume (measured in a graduated container), after multiplying by an empirical factor to take account of inter-grain voids. The grain density so measured typically increases as the grainsize decreases, mainly because smaller grains can only contain the smaller among the population of vesicles.

The significance and utility of grain density is not yet fully explored but it certainly provides information on the vesiculation state and perhaps also the viscosity of the erupted magma, and may reveal the effect of water cooling (cf. Houghton and Wilson, 1989; Bull. Volcanol., 51: 451–462; and Walker, 1992, Pacific Sci., 46: 1–10).

Samples that I collected from Lathrop Wells and Little Cone give grain density plots similar to those of normal-strombolian deposits elsewhere.



Plot of class grain densities against grainsize for a number of basaltic pyroclastic deposits. Samples 1–3 from Lathrop Wells and Little Cone plot in the normal-strombolian field exemplified by Fogo, Etna and Heimaey. Tarawera and Tantalus are plinian and subplinian respectively. Capelinhos, Puu Mahana, Karl and Sandhills are phreatomagmatic. Paricutin is violent strombolian.