REVIEW OF A CONCEPTUAL MODEL AND EVIDENCE FOR TECTONIC CONTROL OF THE GROUND-WATER SYSTEM IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

102

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

REVIEW OF A CONCEPTUAL MODEL AND EVIDENCE FOR TECTONIC CONTROL OF THE GROUNDWATER SYSTEM IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA

EXECUTIVE SUMMARY

This report provides a synthesis of comments by Yucca Mountain Project scientists on a November, 1987, draft manuscript by J. S. Szymanski, titled "Conceptual Considerations of the Death Valley Groundwater System with Special Emphasis on the Adequacy of this System to Accommodate the High-Level Nuclear Waste Repository." Because this preliminary draft was prematurely released and widely distributed, the Project elected to conduct a thorough review and evaluation of the draft, and to document the results of the review in a formal report. The manuscript was therefore evaluated by a large number of reviewers, representing several disciplines, who provided an extensive set of general and specific comments. It is the general conclusion of all of the reviewers that the manuscript at least requires extensive revision by the author, followed by additional review, before the Project should formally release the manuscript. Many reviewers expressed the view that the manuscript has had a constructive effect on the Project by stimulating discussion of alternative hypotheses, although most doubt that there is sufficient technical basis to warrant pursuing the author's hypotheses further.

TREATMENT OF CONCEPTUAL MODELS

Several conceptual models have been developed by the Project and others to describe the physical system existing in the vicinity of Yucca Mountain, forming the bases for numerical models that can be used to quantitatively predict the behavior of the system. Each conceptual model is based on a set of hypotheses about the physical domain and geometry, the key features and properties of the system, the processes and events that may affect behavior, and the boundary conditions. These hypotheses should be consistent with each other and compatible with the available data. However, there is uncertainty associated with the applicability of each conceptual model, and this uncertainty is reflected in the admissibility of alternative models, i.e. more than one set of hypotheses may be both internally consistent and compatible with existing data. One of the principal objectives of the site characterization program is to reduce the uncertainty in the conceptual models of the physical system, particularly those uncertainties most closely related to the ability of the site to isolate waste.

The conceptual model proposed in the draft manuscript differs in several significant ways from the tectonic and hydrologic models currently under investigation by other scientists working on the Yucca Mountain Project. The primary goals of this review report are to summarize the important aspects and consequences of the author's conceptual model, to review interpretations of pertinent data differing from the author's, and to provide recommendations to the author and the U.S. Department of Energy (DOE). The purposes of these recommendations are twofold: (1) to clarify the technical basis and implications of the proposed conceptual model and (2) to ensure that adequate testing will be conducted to provide valid tests of the hypotheses inherent in this model, as well as other conceptual models.

The central thesis of the draft manuscript is that the hydrologic characteristics of the Yucca Mountain region vary, over relatively short periods of time, under the control of tectonic and geothermal forces that originate in the mantle. Regional extension and localized thermal anomalies are hypothesized to act on the fractured rocks and contained groundwater to produce episodic fluctuations of the water table that are of large magnitude. Ongoing tectonic extensional strain is areally well distributed in early stages of the process, resulting in progressive dilation of fractures throughout large volumes of rock. This results in a progressive increase of hydraulic conductivity and storage capacity and a resultant lowering of the water table as strain accumulates in the system. When a sufficiently large extensional strain has accumulated, failure occurs along one or more faults, causing the dilated fractures between faults to close, resulting in a local or regional rise of the water table. In this model, extensional strain becomes localized in the faults at the time of displacement, while compression increases suddenly in the intervening blocks. Fractures in these blocks suddenly close as water is driven to the faults, where, because of increased permeability, it rises. In addition, regional (potentiometric) gradients are hypothesized to increase after major fault events due to a coupled relationship between fracture permeability and stress. The zones of tectonically and geothermally driven upwelling persist for a period of time until drained through residual conductivity, or until continued extension again begins to open fractures, causing the water table to decline and initiating another cycle. A complete cycle may last tens of thousands of years.

EVALUATION OF PROPOSED MODEL

The conceptual model proposed in the manuscript is an alternative to the one described in Chapter 3 of the Site Characterization Plan (DOE, 1988), which considers the flow system to be (1) relatively insensitive to short-term tectonic processes, (2) controlled principally by relatively time-invariant lithologic and structural features of the geologic formations, and (3) driven primarily by gravity flow from recharge to discharge areas. In contrast, the author focuses on the concept of tectonically driven short-term variations in the hydrologic system and contends that other considerations, such as the impact of the lithologic and structural framework of the site on the hydrologic system, and the hydrologic implications of alternative tectonic models, are inconsequential.

The review committee believes that consideration of all important properties and processes is required in a comprehensive hydrologic model, but the model proposed in the manuscript is incomplete. As presented in the draft manuscript, the mathematical formulation is not adequate for numerically estimating the potential magnitudes, frequencies, and durations of the proposed effects.

The author attempts to demonstrate the credibility of the model and the scale of potential effects by showing that its consequences are consistent with contemporary hydrologic features and with the current thermal and in situ stress fields. As noted above, lithology and local and regional structure are assumed by the author to be of minor importance; potentiometric gradients and spatial variations in hydraulic conductivity are ascribed to the spatial variation of in situ stress. Hydrologic interpretations from temperature profiles in boreholes, slug-test data, in situ stress tests, the hydrologic effects of nuclear-weapons tests, and other sources are presented in support of the author's arguments.

It is the opinion of the review committee that the data cited do not, in general, support the interpretations made in the manuscript suggesting a causal relationship between stress and thermal conditions and the hydrologic characteristics of the site. The conventional interpretation of the geophysical and hydraulic behavior in this province is consistent with the available data, and is simpler. However, because data have not been collected specifically to test any of the author's hypotheses, but for other purposes to which his hypotheses are incidental, the committee believes that present data are insufficient to refute rigorously the author's contentions. Many of the data presently available were collected for activities associated with the Nevada Test Site, and not specifically for examining the suitability of Yucca Mountain for nuclear waste storage; the latter purpose is to be served by the site characterization program.

The draft manuscript presents interpretations of field hydrologic and geologic data that differ from those of other Project scientists. For example, the manuscript cites evidence contained in the hydrologic record (e.g., the presence of four proposed hydraulic "mounds") and in the geologic record (e.g., hydrogenic deposits of calcite and silica) as indications of the credibility of the model and of the duration and scale of the effects of its postulated mechanisms.

However, most of the review committee considered the data presented to support the existence of three of the proposed mounds to be unconvincing or incorrect. In general, interpretations of the data made by the original investigators are, in the opinion of this committee, equally or more credible. The possible existence of the fourth proposed mound, in the vicinity of the Greenwater Range east of Death Valley, is acknowledged by reviewers, but several alternatives concerning its origin must be considered. Among these is deep lateral flow of meteoric recharge from distant highlands, as proposed in the original reference. Another, noted by at least one reviewer, is that the Greenwater mound may be related to, rather than coincidental with, the tectonic and igneous environment near Death Valley, the most active extensional area on the continent.

Interpretations of the data pertaining to the ages of the calcite-silica deposits and to temperatures of calcite precipitation are, in several cases, inconsistent with the interpretations made in the cited references. These inconsistencies are not discussed in the draft manuscript. In addition, the author's interpretations concerning the temperature of calcite precipitation are based on obsolete assumptions about the oxygen-isotope composition of infiltrating meteoric water, although conflicting, more modern data are cited by the author elsewhere in the manuscript.

The isotopically determined ages of calcite deposits that are quoted in the manuscript are selected from a larger set of data and are used to support the author's interpretation that the proposed tectonic processes occur in cycles of less than 100,000 yr, probably 20,000 to 35,000 yr. The data cited are of variable quality, but constraints on the quality and use of data contained in the original references are not summarized in the draft manuscript. It is the opinion of most of the reviewers that the data cited generally do not support the cyclic behavior postulated by the author. However, considerable work remains to be done on the dating of the hydrogenic deposits, and the presently available data are insufficient to evaluate the possibility of cyclic behavior, whether related to tectonic or climatic cycles.

There is evidence that water has discharged to the land surface at several localities in the Amargosa Desert and southern Crater Flat within the last 4 million years, although, with currently available evidence, the deposits cannot be shown to be closely correlative in time. They have generally been interpreted in past investigations to indicate cooler, and possibly wetter, climatic conditions than occurred even in Wisconsian time. A water-table position beneath Yucca Mountain that was 80-120 m higher than that existing today is consistent with such conditions. Areally widespread evidence of water levels within this range, if identified, would be considered by most reviewers to be more likely attributable to climatic rather than tectonic processes unless, for example, additional evidence should also indicate upwelling from deep, hydrogeologically unexpected sources.

Although the implications of the author's model with respect to the hydrology of the site are numerous, there are several key aspects and consequences that can be derived from his model. Consideration of the consequences, particularly with respect to the elevation of the water table, has led the reviewers to define three issues, which, if resolved, could provide critical information on the magnitude of potential effects on site behavior and performance. These issues are summarized as follows:

(1) What is the nature and extent of the coupling between tectonic strain, changes of bulk hydraulic properties of the rock, and fluid pressure?

(2) To what extent may thermal processes affect groundwater flow, and particularly the elevation of the water table?

(3) What geologic (field) evidence exists that these processes have, or have not, been active at Yucca Mountain?

More work is clearly needed before final resolution of all of these issues is possible.

CONCLUSIONS AND RECOMMENDATIONS

Extensive revisions are needed in the manuscript to make a credible presentation of an alternative conceptual model. However, despite broad criticism of the manuscript and much of the theory and information proposed in support of the model, reviewers generally agreed that the physical processes considered by the author are among those acting in the earth's crust. Disagreement with the conceptual model focused principally on the magnitude with which tectonic deformation and geothermal processes might affect the hydrologic system and the on author's use of alternative, questionable and selective interpretations of data in place of quantitative evidence for such strong coupling.

The Project's current plans, as expressed in the SCP (DOE, 1988), are considered by the reviewers to adequately address the author's recommendations for analysis of changes in the water table position, for study of the calcite-silica deposits, for chemical investigations of vadose-zone water, and for study of an apparent hydraulic mound in the Greenwater Range. Based on evaluation of the present manuscript, however, the review committee does not recommend delaying other site-characterization activities, nor does the committee currently recommend conducting the study of the Skull Mountain area proposed by the author.

Several additional tests are recommended which, in total, should serve to either increase or decrease confidence not only in the author's conceptual model, but also in those models currently under consideration by others in the Yucca Mountain Project. Calculations with simplified phenomenological models to test the potential significance of tectonic and thermal mechanisms proposed by the author are of high priority. Modifications of testing methods and addition of some investigative techniques are recommended for studies of the natural geothermal field, for hydraulic testing in the saturated zone, for evaluation of large hydraulic gradients near Yucca Mountain, and for studies to evaluate alternative tectonic models. It is also recommended that studies to test the hydraulic, geochemical, and geothermal characteristics of principal faults near Yucca Mountain be expanded.

I. SUMMARY OF REVIEW AND PROJECT RECOMMENDATIONS

A. INTRODUCTION

This report summarizes a technical review of a manuscript completed in November, 1987, as a rough draft by J. S. Szymanski, DOE, Yucca Mountain Project Office. The draft is titled "Conceptual Considerations of the Death Valley Groundwater System with Special Emphasis on the Adequacy of this System to Accommodate the High-Level Nuclear Waste Repository." Throughout this review report, this document will be referred to as "the draft" or "the manuscript" and J. S. Szymanski will be referred to as "the author."

1. MANUSCRIPT STATUS AND REVIEW PROCESS

Before the author could discuss the draft informally with his scientific colleagues, copies were widely distributed outside of the Project. Under less unusual circumstances, a more mature draft would have been formally reviewed in accordance with DOE procedures, and many of the reviewers' comments would not have been necessary. Because of the premature release and the content of the manuscript, however, the Yucca Mountain Project Office elected to subject the draft to a Project Technical Review and to summarize the review results in the present report.

The author's considerations span a large number of specialized scientific fields in the format of a scientific paper. Theoretical considerations in Section 3 of the draft outline a conceptual model in which crustal response to tectonic stress and fluid response to geothermal gradients dominate the behavior of the hydrologic system, in contrast to traditional analyses in which these forces have at most a minor effect over the time interval of interest in waste isolation. In Section 4, hydrologic and geologic data from the Yucca Mountain region are interpreted by the author as showing that his conceptual model is valid, and as demonstrating that fluctuations in the water table large enough to flood the repository horizon have occurred within the geologically recent past. Therefore, the author seriously questions the suitability of Yucca Mountain as a high-level nuclear waste repository site, and he concludes that his conceptual model provides a more accurate basis for assessing site suitability than do traditional geohydrologic models.

Reviewers examined the manuscript as they would one submitted for publication in a scientific journal; rather than merely offering suggestions for improvement, they searched vigorously for evidence to test the hypotheses proposed. Hence, the reviewers produced comments that constitute a rebuttal, as well as a review.

Because it is critically important to ensure the successful isolation of nuclear waste, Project scientists seek an accurate understanding of Yucca Mountain. Thus, they are keenly aware that the burden of proof is on the Project to demonstrate suitability, not upon the author to demonstrate the converse. Accordingly, it seems prudent to regard the draft as an alternative starting point for investigation rather than as an even partially completed scientific study.

Because the draft addresses topics from so many specialties, a somewhat larger than usual number of reviewers was required. The principal reviewers are:

Los Alamos National Laboratory (LANL)
- Bruce M. Crowe
- Kenneth G. Eggert
- David Janecky
- Bryan J. Travis
- David T. Vaniman

Sandia National Laboratories (SNL)
- George E. Barr
- David J. Borns
- Charles R. Carrigan
- T. M. Gerlach
- Elmer A. Klavetter
- William C. Luth
- John Rundle

Science Applications International Corporation (SAIC)/Las Vegas
- Dwayne A. Chesnut
- Terry A. Grant
- Ernest L. Hardin
- August C. Matthusen
- Steven R. Mattson

United States Geological Survey (USGS)
- William W. Dudley, Jr.
- Kenneth F. Fox, Jr.
- Devin Galloway
- David T. Snow (SAIC/Golden)
- John S. Stuckless
- Henri S. Swolfs
- William E. Wilson

Many other Project scientists provided informal input to the reviewers, the author, and the editors of this review report. An attempt has been made in this report to present a synopsis of the reviewers' written comments, as well as an understanding of dialogue between the author and the reviewers in comment resolution meetings.

2. PURPOSE AND ORGANIZATION OF REVIEW

Because the manuscript is an unapproved draft that is officially still in preparation in spite of having been widely distributed and examined, this review report has the following objectives:

1. To advise the Project Office on the status of the draft and the changes that should be made before it can be processed further, and to identify those scientific areas that the reviewers believe need reevaluation.

2. To recommend to the Project Office additions or changes to Project plans that appear justified or prudent as a result of the analysis in the manuscript and of the additional thought that has been stimulated during the review and assessment.

3. To document that the reviewers' opinions currently differ substantially from many of the scientific interpretations expressed in the manuscript and from the resulting implications regarding the suitability of the Yucca Mountain site.

The remainder of Part I summarizes the reviewers' opinions concerning the merits and deficiencies of the manuscript, their recommendations as to further processing of the draft, and their appraisal of its impact on the plans of the Yucca Mountain Project. Section I.B contains criticisms that should be addressed if further processing and eventual formal release of the manuscript are to occur. Section I.C reviews the hydrogeologic and tectonic characteristics of the Yucca Mountain region, presents a summary critique of the principal assumptions and concepts of the author's model, abstracts the detailed reviews of the field evidence that the author proposes in support of the model and from which he draws conclusions about the suitability of the site, and summarizes the principal areas of agreement between the author and the reviewers. Finally, Section I.D evaluates the recommendations to the Project that are made in the concluding section of the manuscript and submits the reviewers' recommended modifications of the Project's plans for site characterization.

Part II presents more detailed syntheses of the reviewers' comments on the scientific aspects of the manuscript, as interpreted, integrated, and, in places, supplemented by the editors of the review report. Although it contains some suggestions for improving the manuscript and identifies some areas of concurrence between the author and the reviewers, Part II is principally a rebuttal and statement of hypotheses and interpretations that differ from the author's.

Comments regarding the scientific and programmatic positions expressed in this review are solicited by the Project Office. They may be addressed to:

Project Manager
Yucca Mountain Project Office
U. S. Department of Energy
Nevada Operations Office
P.O. Box 98158
Las Vegas, NV 89193-8518

B. MAJOR CRITICISMS

1. AUTHOR'S PURPOSE

The author stated in comment resolution meetings that he intended not to develop a definitive scientific treatise, but, rather, to stimulate Project scientists to consider more conceptual alternatives for the behavior of the Yucca Mountain geohydrologic system than are explicitly stated in the Consultation Draft of the Site Characterization Plan (DOE, 1987). When the reviewers challenged the supporting interpretation for some of his concepts, the author pointed out that his manuscript was intended more to raise questions than to answer them. Reviewers generally agree that the manuscript and related discussions have accomplished this purpose.

In the Introduction (Page 1-3) of the manuscript, the author's stated purposes were to "...(1) offer a proposal regarding the relationship between the tectonics of the Yucca Mountain site region and the groundwater flow system ...(in order to)...(2) provoke the initiation of an understanding, on a qualitative or conceptual basis, of this groundwater flow field." The author proposes that "this understanding could then be used: (a) to develop a focused exploration program; (b) to perform a re-evaluation of the existing data and (of the) positions (taken by the Project) based on these data; (c) to develop a description of the natural system; and (d) to develop a rational approach to the performance assessment and the performance allocation process." Because it is an early draft, the manuscript only partially succeeds in presenting the author's concepts clearly enough for the reviewers to understand them without extensive consultation with the author.

In addition to presenting his model, the author suggests that it governs the hydrologic system in the Yucca Mountain area. Most of the draft is aimed at supporting this contention; it also presents a tentative conclusion that assessment of the site in light of the model will show that it is unsuitable. Consequently, most review comments focus on a close examination of the data and arguments presented in support of the conceptual model and the author's tentative conclusions. Generally, the reviewers conclude that many of the author's presentations and interpretations are not supported by the data and that many conclusions drawn are either premature or unwarranted.

In summary, the draft does stimulate the imaginative consideration of alternatives, but it fails to meet other stated and unstated objectives. These could be more nearly met by showing clearly why the author believes a tectonically influenced hydrologic model is needed, followed by a concise rigorous statement of his conceptual model, and by suggestions for estimating the magnitude of the model's consequences.

2. REFERENCE VERIFICATION

The use of references in the manuscript was evaluated both systematically and technically. The systematic verification identified several mechanical deficiencies that are not unexpected in an early-draft stage of a manuscript, such as citations in the text that are not included in the reference list, mismatches between dates of citations in the text and in the list of references and inaccuracies of authorship or titles of references.

The manuscript contains more serious technical problems in citations that are more difficult to identify. For example, data from cited sources have been re-interpreted, but the reader may be left with the impression that the original interpretation is being presented. Sometimes, sources are credited with information that they do not contain. Finally, there are several instances in which the observations or interpretations of original authors have been included directly or almost verbatim in the manuscript without citation.

Reviewers considered selectivity in the choice of references and in the information reported from them to be persistent faults of the manuscript. The author could gain more scientific credibility by acknowledging and evaluating the data and interpretations that are closely relevant to his thesis, including those that conflict with it, and then indicating why he believes his interpretation is to be preferred. Without this comparison and contrast, the author's arguments appear speculative and unconvincing.

3. COMPLETENESS OF ANALYSES

Most of the reviewers were not persuaded that the manuscript demonstrates that the phenomena described are of any significant concern to the Project; i.e., many reviewers concede that the groundwater system is affected by active tectonic processes, but were not convinced that this interaction is likely to be of such scale that it will adversely affect repository performance.

One reason for this reaction is that concepts and observations offered to support them are often introduced only by reference to a figure, without explaining its significance. The text frequently states an intermediate conclusion that is not obviously derived from the figure, but is important to subsequent sections or the conclusions of the manuscript. The manuscript should develop more fully and more rigorously those concepts that are critical to the model and its validation from field data.

Secondly, the author offers no calculations of the possible magnitudes of the effects of the processes he describes. Their significance is first simply implied and later claimed to be demonstrated empirically by hydrologic and geologic features of the region. Reviewers believe that many of the author's interpretations of these features are highly questionable or incorrect. Although this does not necessarily invalidate the model, the model must be developed in sufficient detail to allow scoping predictions to be made of the magnitude of the phenomena described before it can be used in planning or interpreting site characterization activities.

4. COMPLEXITY AND CONTENT

In addition to the need for a more complete treatment in some areas, the manuscript also requires several fundamental changes of content and structure to improve clarity and reduce its length. Several of the subsections in 3 have no obvious relevance to the conceptual development, but they add substantially to the length and to the difficulty in understanding the important aspects of the author's model.

Along with evidence to support the model in Chapter 4, the manuscript contains several tutorials that are not completely consistent with each other nor with concepts expressed in Chapter 3. It is recommended that the various theoretical sections be arranged more logically, examined by the author for internal consistency, and shortened to retain only those sections that are essential to the model. The reviewers seek a concise statement of the factors that the author believes are important to his conceptualization, followed by a direct and rigorous development of the model.

C. MODEL CONCEPTS AND EVIDENCE

Reviewers inferred from the introduction of the manuscript that it is the author's opinion that the Yucca Mountain Project has not considered tectonic stability to be as important as it is for sites where a repository would be constructed below the water table. The proposed Yucca Mountain repository would be constructed within a thick unsaturated (vadose) zone. The manuscript suggests that the Project has accepted some tectonic instability in exchange for the current great depth to water, then questions whether this great depth will persist.

Scientists involved with the Yucca Mountain Project recognize the possibility that the water table could rise if the future climate became very much cooler or wetter (thereby increasing recharge), and studies are planned to quantify this possible rise, as described in Section 8.3.1.5.2 of the Yucca Mountain Site Characterization Plan (SCP) (DOE, 1988). A main tenet of the manuscript is that water might reach the repository from below without a climatic change, in response to tectonic phenomena. The Yucca Mountain Project has planned for some time to evaluate the effects of tectonic events on the hydrologic system. These activities are discussed in Section 8.3.1.8.3 of the SCP, but they do not explicitly address the author's model.

1. HYDROLOGIC MODELS

The concept of a "simple" groundwater flow system is summarized in Section 2.2 of the manuscript, by presentation and discussion of Laplace's equation, Poisson's equation, and a transient flow equation. The transient flow equation is the most general of the three, because the first two equations can be obtained from it merely by setting appropriate terms equal to zero. An important point, made by several reviewers, is that none of these equations allow even "durable" (i.e., invariant in less than geologic time frames) hydraulic properties of the system to vary from point to point. Application of models based on these equations is limited to strictly homogeneous, isotropic media under fully saturated conditions. Despite the author's claims, they do not represent even the simplest models being used for hydrologic studies in the Yucca Mountain region (e.g., Waddell, 1982; Czarnecki and Waddell, 1984; Barr and Miller, 1987).

Currently, most of the reviewers doubt that tectonic and other processes discussed in the draft manuscript will have significant effects on the groundwater system within the next 10,000 yr. However, they recognize that raising such questions is a legitimate and necessary part of the process to determine whether Yucca Mountain is a suitable site for a high-level nuclear waste repository and that the issue of tectonic effects on the hydrologic system must ultimately be investigated and resolved by the Project. Plans to do so are contained in the SCP (DOE, 1988).

2. TECTONIC FRAMEWORK

The author uses the Rio Grande rift zone to illustrate the nature and scale of tectonic and geothermal processes that he proposes are active at Yucca Mountain. In the manuscript, the areal distribution of seismic P-wave velocities and claimed relationships of geothermal parameters to the seismic pattern are presented in support of the hypothesis that mantle convection cells transfer heat into the crust, causing nonuniform heat flow and extensional stresses that are periodically released by faulting.

There are many fundamental structural and geophysical differences that make the Rio Grande rift an unlikely analog to the southern Great Basin (including Yucca Mountain). The supposedly diagnostic seismic pattern of the upper 15 km of the crust near the Nevada Test Site and Yucca Mountain correlates closely with the near-surface distribution of thick, low-velocity volcanic rocks. The distribution of seismic velocities in deeper layers differs from that of the surficial layer, suggesting that the details of the latter are not reflecting mantle influences. Finally, detailed comparison of plates in the manuscript shows that the claimed relationship of heat flow and subsurface temperature with the seismic pattern is, in fact, not consistent with the available data.

Reviewers felt that agreement as to mantle and deep crustal processes is not essential to the concept that the behavior of the hydrologic system is coupled to tectonic stress and crustal temperature. They agreed that the Great Basin is generally an area of crustal extension and areally heterogeneous heat flow, whatever the cause, and they proposed other areas that might be more analogous and useful in developing predictions of tectonic effects on the hydrology of Yucca Mountain.

The manuscript also embraces a theory of fault nucleation and focal-inclusion collapse that was proposed in the 1970's (Brady, 1974; 1975; 1976), but failed to gain acceptance for earthquake prediction after extensive examination by the scientific community. However, reviewers were not aware of any evidence that the mechanisms of Brady's theory have been disproved, despite their apparent lack of diagnostic utility in earthquake prediction. The theory is important, but perhaps not critical, to the author's concept that reduction of pore volume attending focal-inclusion collapse initiates the forceful ejection of deep water, severely dilating the fault zone such that thermal convection can maintain the upwelling even after stress release has occurred. Tentatively, the author's application of Brady's concept was not given credence, though reviewers recommended it be tested with simplified calculational models.

3. CONCEPTS OF THE HYDROLOGIC SYSTEM

The region that includes Yucca Mountain and the Nevada Test Site has been extensively studied for more than three decades. Although there are hundreds of publications describing the geohydrology of the region, the most comprehensive is that of Winograd and Thordarson (1975). Most groundwater recharge occurs in or near upland areas such as Pahute Mesa, the Belted Range, the Spring Mountains, and other elevated areas that receive annual averages of more than 8 inches of precipitation, occurring mostly as winter snowfall. Groundwater beneath Yucca Mountain flows southward to discharge by evapotranspiration in Alkali Flat (Franklin Lake Playa) and possibly, in part, at springs in Death Valley. Other subbasins of the groundwater system, to the east and west, discharge (respectively) in the areas of Ash Meadows and Oasis Valley.

The Yucca Mountain region is complex both structurally and stratigraphically. It contains numerous faults and folds of varying ages, almost no Mesozoic section, and large caldera complexes of mid-Miocene age. Geohydrologic units include Quaternary and Tertiary alluvium, playa deposits, and minor volcanics; Tertiary volcanics; and Paleozoic carbonates and clastics. Regionally, the carbonates (possibly karstic) are the most important aquifers. Locally, however, fractured welded tuffs, the valley-fill alluvium, and even nonwelded tuffs are significant for groundwater flow.

At Yucca Mountain, the present water table is within the tuffs, so there are considerable thicknesses of both water-saturated and unsaturated tuffs. Densely welded units have about 10% matrix porosity and very low matrix permeability, but extensive natural fracturing has made these units highly transmissive. Nonwelded units are not as extensively fractured, but may have relatively large matrix porosity and permeability.

Flow within the vadose zone at Yucca Mountain probably includes small amounts of liquid water from minor local infiltration and a gas phase composed of air and water vapor. In the conceptual model currently favored by many Project hydrologists (Montazer and Wilson, 1984), liquid water flow is believed to be predominantly downward, driven by the force of gravity. Some lateral movement may be possible along geohydrologic unit contacts due to abrupt changes in hydrologic properties. At the currently estimated rate of percolation (less than 0.5 mm/yr at Yucca Mountain), most flow is believed to occur in the matrix of both welded and nonwelded units. If percolation (and consequently matrix saturation) should increase, fracture flow in welded units is expected to become relatively more important. However, these working hypotheses are not fixed concepts, but are merely starting points for the extensive investigations planned for site characterization.

The manuscript indicates that this concept of the hydrologic system is incomplete in ways that may seriously impair the Project's ability to assess site suitability. The author contends that lithologic differences are so much less important than stress-sensitive fracture apertures in determining the permeability and storage distributions controlling groundwater flow within bedrock that he can neglect stratigraphy and structure. Reviewers generally agree that the intensity of fracturing dominates hydrologic behavior in rocks of low matrix permeability. However, the believe that the intensity of fracturing depends upon both the mechanical properties (and hence lithology) and the stress history of the rock units.

Traditional hydrogeology holds that rocks in general become less permeable with depth as pores and fractures close due to the growth of secondary minerals and to the weight of the overburden. At depths determined by the geochemical environment and the mechanical properties of the rocks, the geohydrologic system can be considered, for practical hydrologic purposes, to have a closed boundary that does not permit fluid to enter or leave the system. In those parts of the region around Yucca Mountain that are underlain by the Paleozoic carbonate rocks, the base of the geohydrosphere is assumed by hydrologists to coincide approximately with the deepest base of the carbonate rocks, which may be either structurally repeated or in places missing because of Mesozoic imbricate thrusting or later detachment faulting. In areas where the volcanics are very thick, the base of active flow has not been determined, but significant permeability is present at a depth of at least 3000 m in one test hole on Pahute Mesa (Blankennagel and Weir, 1973). In contrast, the model proposed in the manuscript considers the depth of the effective base of the geohydrosphere to vary in time according to the transient state of stress. Further, it considers the hydrologic system immediately above this base to be significantly influenced by heterogeneous heat flow resulting from relatively local upwelling of the mantle into the crust.

The manuscript uses the widely held view that the Great Basin in general (and the Yucca Mountain region in particular) is being extended tectonically, combined with assumed constitutive relationships for the dependence of fracture apertures on normal effective stress and shear dilation. The concept is developed that the present water-table configuration is strongly influenced by the current stress distribution. Furthermore, the manuscript indicates that the continuing extension expected for this area will determine the future behavior of the water table and possibly cause flooding of the repository level even if the climate remains unchanged.

Although the manuscript addresses principally the behavior of the saturated zone in response to stress, it also states that fracture dilation in the unsaturated zone increases the tendency for flow to occur in fractures. The partitioning of water movement between the rock matrix and fractures is highly significant to the performance of a repository in the unsaturated zone, and the author's statements contrast strongly with those in publications both within and outside of the Project (Montazer and Wilson, 1984; Ross, 1984; Wang and Narasimhan, 1985; Klavetter and Peters, 1986). Because the existing hydraulic gradient is from an unsaturated fracture (at atmospheric pressure) to the rock matrix (with capillary suction), further opening of fractures would not reverse the gradient nor be expected to enhance the opportunity for fracture flow. In contrast, it might increase the opportunity for barometric ventilation of the rock mass, thus enhancing drying and the tendency for the rock mass to imbibe water in fractures. However, the imbibition process may be suppressed by fracture coatings or alteration minerals, which is a possibility that will be evaluated during site characterization.

As understood by the reviewers, the manuscript hypothesizes the following cyclic behavior of the system resulting from ongoing extensional stresses:

1. In the first stage of the cycle, the least principal stress is at its greatest magnitude, corresponding with the recent release of extensional tectonic stress. Fractures are at their residual apertures, producing minimum fracture permeability, maximum slope of the potentiometric surface, and minimum depth to the water table. Normal effective stress increases with depth in a generally linear fashion.

2. As the system is extended tectonically, the normal effective stress is reduced on fractures that intersect the axis of the local least principal stress, particularly on high-angle (near-vertical) fractures. The shear stress along most fractures increases, whereas the resistance to failure decreases as the normal stress is reduced.

3. Eventually, the shear stress approaches the shear strength, which depends upon material properties (e.g., joint cohesion or friction angle) and normal effective stress. Elastic shear dilation occurs until the maximum shear stress is reached, after which the shear deformation and consequent

shear dilation are inelastic. Accumulated shear dilation increases significantly after the onset of inelastic deformation.

4. The net result of these changes (given the validity of the constitutive relationships assumed) divides the geologic section into two regions. The depth to the dividing surface, at which the shear stress has just reached its maximum and inelastic dilation is initiated, increases with time due to continued extension of the system. A condition of "limit equilibrium" is defined by the author to occur above the dividing surface.

5. With continued extension, fractures in the shallower region are increasingly dilated as time progresses. This dilation causes the fracture porosity and permeability, and consequently the depth to the water table, to increase with time.

6. Beneath the dividing surface, hydraulic properties are essentially independent of stress and, therefore, of time. Hydraulic potential in the deeper zone remains higher than that represented by the declining water table, a condition that the author terms "the overpressure."

7. This process is episodically interrupted by movement along one or more normal faults, allowing the accumulated, spatially distributed extensional strain to be concentrated in the fault zones. In the crust between the faults, the least principal stress increases and the water-table altitude rises due to the reduction of storage volume in the fractures; hydraulic gradients increase to accommodate the groundwater flux with reduced permeability. There may also be coseismic upwelling of water along the fault zones, which might continue for tens to hundreds of years due to thermal convection. The potentiometric levels above the previous dividing surface of limit equilibrium exceed those below; this results, according to the author, in the existence of "the underpressure" at depth.

8. The cycle repeats every few tens of thousands of years as long as extension continues in response to thermal gradients.

The development of this conceptual model in the manuscript is lengthy and complex. Many of the mechanical concepts and constitutive relationships that are proposed are not integrated into the overall model, and they are not accompanied by physical coefficients that allow estimates of the effects of even the component processes.

Reviewers commonly expressed opinions that the basic processes are credible at some currently undefined level of significance, but that this level, if actually calculated, would probably be minor to trivial. Among the specific criticisms are the following:

1. The manuscript does not distinguish between fluid-pressure response to changes of fracture aperture in a hydraulically confined system and a change of the unconfined water-table position, in which substantial quantities of water must move into previously unsaturated fractures or be drained from previously saturated ones. The differences between confined and unconfined hydraulic responses should be carefully recognized in the revised manuscript.

2. Changes of pressure due to fracture deformation would be substantially attenuated by the hydraulic diffusivity of the rock matrix. The same would be true for changes of water-table position, although the rock-matrix response would be much slower because of the small permeability of the matrix relative to the fracture system. There is abundant field evidence from test holes at the NTS and elsewhere that rocks of low permeability at or near the greatest depths of exploration will recover from hydraulic disturbances within hours or days. Larger affected volumes, such as those in zones of explosion-stimulated aftershocks or tectonic adjustment, recover within days or weeks. The revised manuscript should include relationships between effective stress and hydraulic diffusivity for both fracture and matrix domains, in order to allow approximate calculations of the rates at which fluid-pressure disturbances would dissipate.

3. Both vertical and lateral gradients of hydraulic potential are the expected result of flow (and, hence, energy consumption) even in uniform, isotropic media. Geologic complexity causes additional complexity in the spatial distribution of hydraulic potential. Most of the large hydraulic gradients occur across low-permeability units interspersed with low-gradient segments through high permeability rocks such as carbonates. It is appropriate to evaluate changes of regional piezometry occasioned by stress-coupled changes of permeability in the tight rocks.

4. Some reviewers inferred that thermal upwelling is proposed to provide sufficient fluid pressure to maintain the opening of faults against the least principal stress. Given the relatively weak forces of thermal buoyancy, this is not considered credible, however the existence of conductive faults at considerable depth is accepted as a possibility. Seismic events themselves indicate that accumulated extensional strain is accommodated by structural repositioning of rocks that are still in contact across fault zones, as do fault breccias and gouges. The manuscript does not provide analyses to demonstrate the credibility of thermally driven upwelling or upward seismic pumping for sustained periods.

4. PROPOSED EVIDENCE FOR MODEL

Section 4 of the manuscript proposes several types of observations in the field to support the contention that the conceptual model is acting in the vicinity of Yucca Mountain and that the effects are indeed significant. The proposed evidence is examined critically and in detail in Section II of this document. Results of this examination are summarized in the following subsections.

a. <u>Potentiometric and Thermal Gradients</u>

As discussed previously, the author assumes that the variation of inherent or "durable" hydraulic properties of the rocks in the Yucca Mountain region is not important in comparison with the effects of tectonic stresses on fracture apertures. Though less explicitly, the author also considers bulk thermal conductivity of the rock mass to be stress-controlled due to the effect of convective heat transport by flow of water in fractures. Both lateral and vertical gradients of hydraulic potential and of temperature or calculated heat flow are thereby influenced principally by stress. Reviewers agreed that stress probably affects the permeability of fractures to some degree and that the regional stress field may contribute noticeably to regional hydraulic anisotropy. However, there are numerous examples where large potentiometric gradients are associated with hydrogeologic boundaries. Hundreds of hydraulic tests at and near the Nevada Test Site have demonstrated that effective permeability is strongly related to rock types, particularly their geologic history and susceptibility to fracturing, and that hydraulic gradients are similarly related (Winograd and Thordarson, 1968; 1975; Blankennagel and Weir, 1973). The abrupt southeastward decline of the regional potentiometric surface along a trend from Beatty northeastward past northern Yucca Flat corresponds to the lateral transition of flow from moderately welded and poorly permeable volcanic and clastic rocks into more permeable welded-tuff, alluvial, and carbonate aquifers.

In Yucca Flat, the manuscript describes the water table as including hydraulic mounds and sinks in accordance with contours from a field-trip guidebook compiled by Corchary and Dinwiddie (1976), but fails to note that these are contoured interpretatively based on very sparse data and on observed effects of underground nuclear explosions on the enclosing rocks. The author does not acknowledge and challenge explanations of these effects published in studies of both weapons testing and Plowshare experiments (Borg et al., 1976; Claassen, 1978; Doty and Thordarson, 1983; Buddemeier and Isherwood, 1985).

The water table at Yucca Mountain is also presented as reflecting in situ stress conditions, but its configuration does not appear to correlate well with the limited existing stress data. The Project has made provision in the Site Characterization Plan to investigate the cause of the large hydraulic gradients from the north and west. Reviewers expect that the areas where the gradient is steep will be found to be underlain by rocks of low fracture conductivity, as compared with those beneath most of the proposed repository site and areas to the east and south of the site. Discrete barriers, such as faults containing gouge, are also considered to be a possibility.

As also discussed previously, lateral differences of heat flow and subsurface temperatures did not correlate with seismic-velocity patterns, as claimed in the manuscript. Further, the scale of temperature variations is smaller than can be explained readily in terms of mantle convection or the positions of known major faults. Many reviewers proposed that the short-wavelength lateral variations are more likely to be caused by differences in the thermal conductivity of rocks, by convective heat transport due to recharge-driven groundwater flow, or by vaporization and advective removal of heat from the thick sections of unsaturated rock (Sass et al., 1988).

Changes of hydraulic potential (head) with depth at Pahute Mesa, Yucca Flat, and Yucca Mountain are similarly proposed to demonstrate the influence of in situ stress. The manuscript presents highly idealized relationships of head to depth, representing these relationships as portrayals of the field data and as being consistent with the author's concepts of "overpressure" and "underpressure" beneath a surface of limit equilibrium. However, the actual field data display more complex patterns, including reversals of gradient direction that have been explained in terms of durable hydrogeologic features (Winograd and Thordarson, 1975; Blankennagel and Weir, 1973), and which appear to reviewers to be incompatible with the proposed conceptual model.

Inflections of temperature profiles in boreholes are also attributed in the manuscript to conditions of stress, though without explanation of the causative mechanism. Some of the examples offered, and other similar occurrences, have been confirmed by borehole flow surveys and detailed head measurements to demonstrate uphole or downhole flow after drilled connection of zones with differing heads. In cases where the flow is uphole, the measured head differences are commonly greater than could be attributed to differences in the relative density of the water. As is true for reversals of potentiometric gradients, both uphole and downhole flow have been observed at different levels in the same borehole at Pahute Mesa (Blankennagel and Weir, 1973), a phenomenon which is difficult to reconcile with fundamental control of hydraulic parameters by stress.

b. Groundwater Mounds

The conceptual model presented in the manuscript suggests that there should be expression of active or former thermal- or stress-driven mounding of the water table. Criteria are presented, but they are not sufficiently specific to distinguish unambiguously between perched infiltrating water and relict mounds, or between active mounds (i.e., formed by upwelling water) driven by fracture closure and those driven by purely hydraulic gradients in an unchanging fracture system.

The author states in discussing his Plate 4.2-1 that springs around Beatty, Nevada discharge at elevations above 4000 feet, which is at least 200 feet above the water table elevation five miles north of Beatty. He also presents a table from White (1979), containing discharge temperatures and chemical analyses of water flowing from a number of springs around Beatty, but does not indicate how these data relate to the presence or absence of a groundwater mound. Consequently, reviewers did not agree that these observations "clearly" and "in no uncertain terms" demonstrate the presence of a deep rooted hydraulic mound. During comment resolution meetings, much of the support for the mound was found to be a result of the author's misreading elevation data, and most reviewers consequently dismissed the idea of a mound at Beatty.

The author proposes an actively upwelling mound in the vicinity of Skull Mountain at the Nevada Test Site. The possibility of even a relict mound seems to be precluded by the chemical data, which do not support a common source for highly mineralized water in the various zones. The opinion of the cited authors i.e., Winograd and Thordarson (1975), though not challenged nor discussed in the manuscript, is that the occurrences represent meteoric waters that are temporarily (in geologic time) perched in their downward percolation through the vadose zone, and most reviewers preferred this interpretation over the author's.

Rainier Mesa (on the Nevada Test Site) has been subjected to repeated short-term stresses by numerous, though relatively small, nuclear tests. The author bases his conclusion that the area is one of relict mounding principally on water-chemistry data that are presented selectively from a larger data set reported by Winograd and Thordarson (1975). The entire data set for undisturbed water in the region shows that the samples from Rainier Mesa had among the lowest (rather than relatively high, as stated by the author) concentrations of dissolved solids and sulfate (Table II.E-1). However, episodic increases of TDS, sulfates and other constituents do occur for short periods after nuclear explosions at Rainier Mesa. Reviewers noted that elevated concentrations of most constituents in water released from rocks subjected to explosive compression are an expected consequence of slow groundwater flow through the rock matrix, with attendant long periods for chemical reactions to occur.

At a recent meeting of the American Geophysical Union, Czarnecki (1987) presented limited evidence for a groundwater divide (or mound) beneath the Greenwater Range, between the southern Amargosa Desert and Death Valley. In the manuscript, the occurrence of this feature is portrayed as being attributable only to anomalously high local recharge or to stress-driven mounding. Although he discussed the possibility of high present or past recharge, Czarnecki (1987) offered the primary explanation that water recharged in distant uplands, probably the Spring Mountains, circulates in the regional carbonate aquifer deep beneath the southern Amargosa Desert and rises along fault zones in the Greenwater Range, eventually discharging at springs in Death Valley. This explanation is consistent with the observed high temperatures (~70°C) and apparent upward gradients (Czarnecki, 1987), and with the earlier speculations of Winograd and Thordarson (1975), who lacked the recently acquired data, that only part of the flow in the carbonate aquifer discharges at Ash Meadows, the remainder continuing along deep flow paths toward Death Valley. They proposed this, in part, from water-budget considerations (balancing of recharge and discharge), not from observations of excess discharge that would require an ongoing reduction of storage in the groundwater reservoir. However, confirmation of this explanation could be obtained only by demonstrating (by drilling and testing several wells) the existence of a deep artesian aquifer beneath the southern Amargosa Desert, with a head greater those observed in the Greenwater area; even this would not completely rule out the mechanisms envisioned by the author.

c. <u>Mechanical and Hydraulic Response to Stress</u>

Reviewers reacted less negatively to the sections addressing in situ stress, results of hydraulic slug tests, and response to underground nuclear explosions than to other sections addressing the field evidence. This is because the fundamental concept that the mechanical and hydraulic systems are coupled is not in dispute. The principal criticism of these sections is that the author overinterprets the data in terms of shear failure and resultant dilation of the rock mass. As a consequence of underground nuclear explosions, shear failure undoubtedly occurs, but its durable hydrologic effects are overwhelmed by stronger and more persistent compaction that reduces rather than increases porosity and permeability out to several cavity radii from the explosion cavity. In situ stress (hydrofrac) and slug tests do not allow differentiation between shear displacement and normal displacement of the fracture faces. Hence, the validity of the author's proposed constitutive relationship between stress and hydraulic response cannot be assessed from the field data. Since they affect only a small region around the well bore, it is difficult to extrapolate behavior observed in these tests to the scale that would be significant in terms of the author's conceptual model.

The slug-test data reveal considerable variability (several orders of magnitude) in the vertical distribution of permeability. If the author's thesis that the state of stress is the principal control on permeability were to be accepted, then it must also be accepted that stress is highly variable over short vertical distances. Furthermore, the author's interpretation of the slug-test data implies that the most permeable zones are the most extended, with large changes of fracture aperture attending changes of effective stress; this corresponds with the author's Type D curve on Plate 4.7.4-3, for which only a small increment of fluid pressure is required to meet the Griffith criterion for tensile failure. In contrast, actual test data show that the more permeable zones exhibit transmissivities under pumping (drawdown) conditions (in which effective stress is increased) that are similar to those determined under injection conditions (in which effective stress is reduced). Thus, the data suggest that zones of small to moderate, rather than large, permeability are the most susceptible to fracture dilation under large injection pressures.

The author's explanations of post-explosion hydraulic effects contrast markedly with understanding of these phenomena that has been developed in siting and safety studies of underground nuclear-weapons tests and in evaluating the enhancement of permeability of tight rocks for recovery of oil and gas in the Plowshare Program (see Borg et al. (1976) and Buddemeier and Isherwood (1985) for reviews of the literature on this topic). The author proposes that the post-explosion hydraulic effects of the Bilby event at Yucca Flat can be explained by the following sequence:

(1) "perturbation in the in situ strain energy field" results from shock-induced increases of fluid pressure, which diminish with distance from the explosion site;

(2) dilation of fractures and consequent increase of vertical hydraulic conductivity locally around the detonation site occur in response to the large fluid overpressure, transferring compressive strain outward from the site and allowing water to drain downward into zones having lower hydraulic potential or head; and

(3) retransfer of strain from "the rebellious volume of the fractured medium" inward toward the explosion site reduces fracture apertures and hydraulic conductivity and initiates a gradual recovery of the water table at the site.

A similar sequence is proposed to explain the hydraulic effects observed in drillholes within several kilometers of the Handley explosion at Pahute Mesa. The author offers the alternatives that the initial post-explosion increases of fluid potential reflect hydraulic communication with zones of higher head at depth, or that they indicate decreases of hydraulic conductivity and storativity attending closure of fractures during shock-induced restructuring of the strain-energy field. In either case, the final stage of recovery is presumed similar to that described for the "rebellious" volume around the Bilby site in that fluid pressures were too high relative to rock mass stress, thus forcing fractures open, in turn allowing dissipation of the fluid overpressure and reclosing of the fractures. The author contends that the "process repeated itself over and over again until the system found a new equilibrium configuration" (i. e., an oscillatory interaction of fluid pressure and rock mass stress).

The existing understanding of close-in phenomena, as accepted by scientists in the defense and Plowshare programs (Borg et al., 1976), is that the initial explosion cavity is formed by melting, vaporization, and intense compression of the rock mass and its contained water, and, in part, by doming of the overlying land surface. With the decline of gas pressure in the cavity, the roof collapses and upward stoping forms a "chimney" in which the original cavity volume is distributed between blocks of rubble and, if stoping continues upward to the surface, in the volume of the subsidence or collapse sink. The post-collapse drop of the water level results from the sudden increase of interblock porosity, not from downward draining through the solidified rockmelt puddle and intensely compacted rocks. At the Bilby site, U3cn-PS#5 was drilled into the Paleozoic rocks beneath the explosion cavity and was pumped for several years. If the author's hypothesis were correct, tritium and other radionuclides should have been present in the pumped water, but they were not detected (Buddemeier et al., 1985).

The author's hypotheses for observations away from the immediate explosion sites fail to explain the delay of weeks to months before the "rebellious" rock mass elastically transferred compressional strain back to the explosion sites, reclosing vertical fractures. In the case of Handley, the claimed cyclic change in the role of water from reactive to proactive, with periodicities of at least days to weeks, was not observed in the potentiometric data. Oscillatory, inertial reactions of wells (or of sinkholes acting as piezometers) to both hydraulically and mechanically imposed stresses are known occurrences, but they occur with periods measured in seconds to tens of seconds (Bredehoeft et al., 1966; Cooper et al., 1965; Dudley et al., 1971; Dudley and Larson, 1976). Elastic recovery of a mechanically strained, saturated rock mass would be damped by the requirement to transfer fluid as porosity changes, resulting in decay of strain accompanied by a reactive change of fluid pressure.

The post-Handley hydraulic effects appear to be consistent with fluid-pressure reactions to explosion-induced adjustments of tectonic strain, as was proposed by Dudley et al. (1971). That such adjustments occur and that they result in a coupled response of the groundwater system are not in dispute. However, reviewers did not accept the author's more detailed causative explanation, and they questioned the relevance of the explosion-induced effects to natural tectonic phenomena.

d. Geologic Record

If the processes proposed in the manuscript act at rates and magnitudes that would be significant within the required performance period for a repository, the geologic record should contain evidence of former elevated positions of the water table or evidence of hydrothermal upwelling. Evidence is proposed by the author for the cyclic occurrence of these processes in Late Pliocene and Quaternary times and for the formation of calcite veins at temperatures higher than those prevailing at the present time.

Ages reported for calcite deposits in the Yucca Mountain area (Szabo et al., 1981; Szabo and Kyser, 1985; Szabo and O'Malley, 1985) are based principally on uranium-series (U-series) dating, a well established technique that, nonetheless, has limited application for some types of deposits. Limitations arise from difficulties in laboratory separation of mixed samples and from syndepositional and post-depositional geochemical processes, such as mobilization of diagnostic isotopes in geochemically open systems. The sources cited in the manuscript state the precautions with respect to certain samples, and they emphasize that ages determined for some samples are lower bounds and perhaps much younger than actual. Nonetheless, these minimum ages receive much greater emphasis in the manuscript than the larger set of greater ages. In addition, ages for associated non-calcite materials and stratigraphic relationships that conflict with the minimum ages are frequently not reported by the author.

i. Calcite and Opaline-Silica Deposits

Calcite occurs at several localities throughout the region as dense veins in faults and fractures, commonly with associated opal. Whereas most Project scientists who have studied these deposits in detail tentatively consider them to originate from infiltration or pedogenic processes, the author considers them to be very strong evidence for hydrothermal upwelling as the mode of deposition. Similarly, an erosional exposure in a sand ramp at Fran Ridge is considered by the author to be a vein deposit and travertine "apron" draped over the now-buried paleosurface, but Project scientists interpret it as a probable pedogenic calcrete. Mineralogically and isotopically, the Fran Ridge deposit is very similar to the vein calcite at Trench 14, suggesting a similar origin.

The author extracts temperatures of calcite precipitation from reported $\delta^{18}O$ values for the calcite and from assumed values for $\delta^{18}O$ (-9°/oo) of source waters (Szabo and Kyser, 1985). He concludes that the veins formed at temperatures 5 to 8 °C higher than those prevailing today at equivalent depths and that the paleothermal gradient was correspondingly higher. Reviewers pointed out that convincing evidence became available in the mid-1980's that $\delta^{18}O$ values for groundwater in the region during the past 250 Ka range from -12.4 to -13.8 °/oo (Claassen, 1985; Winograd et al., 1985). In fact, a similar range, reported by Russell (1987), is included in the manuscript for water in the vadose zone at Rainier Mesa. Recalculation of calcite-precipitation temperatures using this range results in surface temperatures of 2 to 17°C, which is interpreted to be consistent with a meteoric source for water precipitating the calcites in the near-surface vadose zone under cooler, possibly wetter conditions than currently exist.

It is conceded in the manuscript that the calcite veins at Trench 14 are older than 100,000 yr, and possibly older than 1,000,000 yr. Basaltic ash has been found within fissures at four fault zones, including Trench 14. Several of these fissures cut late Pleistocene surficial deposits, and it is thus likely that the source of the ash was the (late Pleistocene to Holocene?) Lathrop Wells volcanic center, and not the middle Pleistocene basaltic vents (dated at 1.2 Ma) in central Crater Flat. Because the youngest known eruption at Lathrop Wells cone was of small volume, the likely age of the ash infilling is less than 250 ka but older than Holocene. At other calcite-vein localities, minimum ages of >400 ka from both calcite and opal (Szabo and Kyser, 1985; Szabo and O'Malley, 1985) are not discussed, whereas much younger u-series ages that are considered explicitly (in the cited papers) to be minimal estimates are emphasized.

The author does not propose a source of water that could precipitate the calcite, but reviewers propose the lower carbonate aquifer (Lower and Middle Paleozoic limestone and dolomite) as the only significant known source of groundwater with abundances of calcium and bicarbonate. Water sampled from the aquifer near Yucca Mountain has a temperature of 54 to 57°C and a $\delta^{13}C$ value of -2.3 °/oo (Benson and McKinley, 1985), and $\delta^{13}C$ values as low as -5 °/oo are reported by Claassen (1985) for other water from the carbonate aquifer. Mixtures of rainwater ($\delta^{13}C$ of -8 °/oo), pedogenic water ($\delta^{13}C$ of -4 °/oo to 0), and water from these deep sources are consistent with the $\delta^{13}C$ values for the calcite, -4 °/oo to less than -8 °/oo. More data from the vicinity of Yucca Mountain would be necessary to determine the source.

Reviewers also questioned the likelihood that water originating at depth at temperatures of 54°C or higher could be mechanically or thermally forced upward through faults at diverse locations and rise to diverse altitudes; that it could coincidentally cool to the narrow range of 20 to 25°C, as stated in the manuscript (17°C is a more likely upper temperature limit because of constraints on water composition), just below the land surface; and that it also would fail to discharge at the surface at rates that would deposit travertine terraces, such as have been preserved for 1 million years in Death Valley in association with an area of acknowledged spring discharge.

In support of the concept of forceful hydrothermal upwelling, the manuscript describes silica-cemented breccias in the wallrock of the Bow Ridge and other faults as probable "explosion breccias". Project scientists have not reached a consensus regarding their origin, but they believe from field relationships exposed at and near Trench 14 that the breccias formed during early (i.e., late Miocene) stages of fault development, in a tectonic environment much different from that existing today.

Vein-calcite deposits along the Cane Spring fault are considered by reviewers to be similar to those near Yucca Mountain and probably of meteoric, pedogenic, or perched-spring origin. Deposits of gypsum at Wahmonie are acknowledged to be different, but a "recent" age, as claimed in the manuscript, cannot be substantiated. The gypsum deposits are believed to be much older, probably associated with late-stage alteration accompanying a Miocene episode of silicic volcanism in the Wahmonie area. The need for further study of these deposits is recognized by Project scientists.

ii. Former Water-Table Altitude

Calcite mounds at Crater Flat, which are interpreted by the author and tentatively by Project scientists as spring deposits, are proposed in the manuscript as evidence that the water table near Yucca Mountain stood at an altitude of 940 m in the Pliocene or Pleistocene. This is about 210 m higher than the current regional water table, which stands at about 730 m altitude beneath central Yucca Mountain, Fortymile Wash, and the northern Amargosa Desert.

However, the altitude of 940 m is based on a sampling locality that is not in Crater Flat but, rather, is on the southward extension of Yucca Mountain, on a low divide between Crater Flat and Fortymile Wash. In the cited reference (Szabo et al., 1981), the deposit is described as a "seep-deposited tufa or calcrete intercalated in Q2 alluvium." This original description and the occurrence of the deposit in association with stratified volcanic rocks of various hydraulic properties leads the reviewers to favor an origin at a perched spring or as a pedogenic calcrete. The need for a more comprehensive evaluation of this locality is recognized.

In southern Crater Flat, apparent subaqueous spring deposits of nodular tufa occur at an altitude of about 840 m (about 100 m above the present water table), in association with sediments believed (Swadley and Carr, 1987) to have been deposited in a marsh or shallow pond. At a nearby locality along a present channel, the sediments are exposed at an altitude of about 854 m, suggesting groundwater discharge about 115 m above the present water table. Ages of the deposits are not well constrained, ranging from "η30,000" years (Szabo et al., 1981) to older than a few hundred thousand years, based on stratigraphic relationships.

Similar sediments about 3 km to the south contain vertebrate and invertebrate fossils that suggest, respectively, ages of less than 2 m.y. (Swadley and Carr, 1987) and early to middle Pleistocene (Forester, 1979). The fossil assemblage is consistent with a shallow pond or pool environment with a considerable seasonal range of temperature. These deposits occur at altitudes up to 800 m, about 80 m above the underlying current water table.

The thick alluvium of lower Fortymile Wash and the Amargosa Desert is highly transmissive (Waddell et al., 1984; Czarnecki and Waddell, 1984). It is therefore likely that the 800 m altitude is an approximate upper limit for a late Pliocene to mid-Pleistocene water table near the mouth of Fortymile wash. Along Fortymile Wash in northern Jackass Flats, welded tuffs (Topopah Spring Member) provide large transmissivities at two water-supply wells. The small potentiometric difference (less than 10m) between these localities indicates a continuum of large transmissivity. The similarly small gradient from central Yucca Mountain into northwestern Jackass Flats indicates that the entire flow path from the proposed repository site to the northern Amargosa Desert is highly transmissive. Climatic conditions that may have caused a rise of 115 m or more of the water table at southern Crater Flat therefore seem unlikely to have produced a rise of the same magnitude at Yucca Mountain. Although the gradient from central Yucca Mountain to the northern Amargosa Desert would probably have been somewhat greater than at present, the accompanying increase of saturated thickness, including greater saturation of eastward-dipping Topopah Spring welded tuff, would also have increased transmissivity. A rise of the water table between 80 m and 120 m at Yucca Mountain probably occurred at some time between the late Pliocene and middle Pleistocene under cooler or wetter climatic conditions. Climatic, rather than tectonic, causes would suffice to explain evidence for a water-table rise in this range.

It is apparent that intensive study of Crater Flat and Amargosa Desert marsh-like deposits and apparent tufas is important for two reasons: (1) to determine that they record a different climate rather than hydrothermal upwelling from deep sources; (2) to establish that the range of 80 m to 120 m is a reasonable estimate for the maximum climate-induced rise of the water table beneath Yucca Mountain.

D. CONCLUSIONS AND RECOMMENDATIONS

The manuscript requires extensive editing and a careful attempt by the author to delete information and analyses that contribute little to the development or the evaluation of his conceptual model. More importantly, rigorous development of the mechanical and thermal consequences of the model is required so that its significance can be tested. If significant effects can be demonstrated or even strongly suggested, the model could be applied in performance allocation and performance assessment.

A more balanced presentation of data offered to support the model is essential if the manuscript is to be offered as a scientific report or paper. This requires that data be presented in the context of all pertinent information in the source references and that interpretations of the original authors be acknowledged, summarized, and discussed so that the reader clearly understands why the author thinks an alternative explanation is required.

Despite broad criticism of the manuscript and rebuttal of much of the theory and information proposed in support of the model, reviewers generally agreed that the physical processes invoked by the author are among those acting in the earth's crust. Disagreement with the conceptual model focused principally on the scale at which such processes might affect the hydrologic system; most reviewers expressed opinions that the effects are small in comparison with those of traditionally recognized hydrogeologic and recharge-driven potentiometric factors. Reviewers agreed that coupling of the hydraulic and rock-mechanical systems is evident in the effects of nuclear explosions and in those of hydraulic-stress tests in boreholes, but details of the author's explanations were challenged in many instances.

Proposed hydrologic evidence for relict mounds of the water table was discounted in favor of earlier interpretations, involving perching of infiltrating meteoric waters, which reviewers believed to be more consistent with the data. The criteria for recognition of actively upwelling water were judged to be ambiguous because the upward potentiometric gradient could result from either fracture closure or spatially variable, temporally fixed hydrologic parameters.

The geologic record that has so far been discovered does not support an interpretation that the Quaternary (and late Pliocene?) water table beneath Yucca Mountain exceeded its present altitude by more than about 100 ± 20 m; moreover, the geologic record in southern Crater Flat and the Amargosa Desert, although incomplete, currently favors an interpretation that such a rise was climatic rather than hydrothermal in origin. Similarly, evidence pertaining to the origin of the calcite veins and caliche weighs in favor of precipitation from infiltrating water in a cooler environment, rather than in favor of hydrothermal upwelling of deep water. The Project does not consider these issues to be closed, and it has planned extensive investigations to increase confidence in the current, tentative interpretations.

The author recommends four investigations to be completed before the commitment of substantial resources for site characterization. With the exception of the study of the postulated Skull Mountain mound, these investigations have been under way for some time and are planned for continuation. They are discussed briefly below.

1. Analysis of Water-Table Position:
   The Project has monitored water levels at Yucca Mountain since completion of the first borehole a decade ago and has added systematically to the observation-well network since then. The purposes are to define the present-day water-table configuration, to define the sustained and temporal relationships of potentiometric levels of deeper zones to the water-table position, and to detect and interpret both short- and long-term changes. The present data do not allow confident detection of long-term trends, but steps are being taken to improve the instrumentation. Analysis of data to evaluate short-term changes is under way, including the evaluation of instrumental, climatic, and seismic-response effects. Preliminary indications are that some potentiometric excursions will not be explained by those effects, and that they well may reveal strain events. The occurrence of strain-related excursions would not be considered surprising, but their magnitudes would be of great interest. Consideration is also being given to installing borehole strain meters to enhance the study.

2. Calcite-Silica Deposits:
   Studies of the paleohydrology of the Yucca Mountain area also began more than a decade ago, and extensive further studies are described in the Site Characterization Plan and detailed in a study plan that is presently in review. Investigation of the ages and possible origins of the calcite-silica deposits is an important and explicit component of these plans, consistent with the author's advice that the Project must establish a firm position as to whether flooding of the repository is an anticipated event, as defined in the pertinent regulations.

3. Chemistry of Vadose-Zone Water:
   Investigation of the chemistry of vadose-zone water at Yucca Mountain has been under way for several years, as borehole access has been available, and extensive further sampling is planned both by drilling and in the exploratory shaft. Completed holes (UZ-series) were drilled with air and with provisions for stopping and sampling free water if encountered; these are included also in plans for future drilling. However, the reviewers disagree with the author's interpretation that the mere occurrence of perched water demonstrates hydrotectonic mounding, rather than infiltration of meteoric water, and believe that the chemical criteria proposed for detecting mounded water in rock interstices are not specific enough to be useful. Isotopic and chemical-kinetics studies are considered more likely to produce diagnostic evidence.

4. Investigation of Perched Waters (Mounds):
   In the opinions of the reviewers who commented on the manuscript section regarding the Skull Mountain mound, the evidence and analysis were unconvincing, and do not warrant expanded study of this area.

   Mounding of the saturated zone, not perching in the vadose zone, in the Greenwater Range was proposed in the cited abstract for an American Geophysical Union poster session by Czarnecki (1987). The data that are currently available satisfy the manuscript's criteria for active hydro-tectonic mounding, but they equally satisfy the criteria for recharge-driven mounding. The Project plans to investigate the

Amargosa-Greenwater area further with hydrogeologic, hydraulic, thermal, and hydrochemical (including isotopic) methods in order to evaluate the significance of the apparent groundwater divide to the regional hydrologic setting of Yucca Mountain. However, assuming that an upward hydraulic gradient is verified, the investigation is unlikely to produce information that could unequivocally identify the cause of the gradient. An exception would be the identification of solution-enlarged, hence undeformable, fractures in an aquifer having large diffusivity. In that case, stress-induced deformation could be ruled out with considerable confidence.

During evaluation of the manuscript, reviewers identified other activities and modifications of currently planned activities that would enhance the Project's ability to evaluate the likelihood that the author's model functions with potentially significant effects on the hydrology of Yucca Mountain. Specific areas where plans are recommended to be developed or modified are as follows:

1. Calculations with simplified phenomenological models should be undertaken to establish the magnitudes of both potentiometric and water-table response to physically possible ranges of stress changes, and to establish the limitations of thermal buoyancy in producing upwelling of water in fault zones.

2. The quality of geothermal data needs to be improved by completion of boreholes in a manner that provides good thermal coupling with the rock mass and that will preclude flow of water or air in the artificial pathway afforded by the hole itself. Current practices impede accurate characterization and confident interpretation of the thermal field at Yucca Mountain. An additional temperature log should be obtained soon in UE25p-#1, and remedial plugging of the annulus between the casing and the borehole wall above the carbonate aquifer should be considered.

3. Hydraulic head determinations by measurement of water levels in tubing above zones isolated by inflatable packers should, in many cases be corrected for the relative density of water in the tubing, requiring temperature logs in conjunction with the measurements.

4. Plans for hydraulic testing by injection methods should recognize that fracture dilation can occur at injection pressures exceeding the least principal stress. Further, the conditions for shear failure are exceeded at lower pressures, although it is believed that lateral restraint of the rock mass prevents shear motion. Testing should include ranges of both positive and negative hydraulic stresses to investigate further the coupling of mechanical and hydraulic stresses and to provide by-product information on the distribution of in situ stress.

5. Plans for study of post-closure hydrologic effects of tectonism and geothermal processes may require more explicit recognition of the differing effects of alternative tectonic models. They may also require more emphasis on supporting investigations, such as in situ stress, thermal, and geophysical studies, than would be indicated by the needs for their use to support pre-closure considerations alone.

6. Completion of hydrologic holes to investigate hydraulic characteristics of faults of different styles and orientations should be considered in future planning. Long-term monitoring of fluid pressures, water-table positions, and rock-mass strain in such holes is also recommended.

7. Geologic and hydrologic investigations of the large hydraulic gradients north and west of the site should include in situ stress and thermal studies. Further, investigation of the hydraulic relationship of Yucca Mountain to Crater Flat is needed to evaluate the significance of the evidence of probable spring discharge in southern Crater Flat in Plio-Pleistocene time.

8. Temperature data and heat-flow calculations for UE25a-#3 should be re-evaluated and assessed as to possible significance. Further work in this area may be recommended.

We believe that current planning otherwise addresses adequately those studies needed to distinguish among alternative tectonic and hydrogeologic models, as well as those needed to evaluate hydrogenic deposits of calcite, silica, and associated materials. We caution, however, that the reader should not interpret this to mean that the Project considers plans to be unalterable. The recommended studies involve interdisciplinary considerations that lie beyond the normal bounds of expertise of individual specialists, and results may force the reassessment of assumptions and approaches. Accordingly, there should be a periodic, at least annual, internal review of results and ideas, and interchange of results, to provide sufficient feedback among Project scientists to allow readjusting the emphasis of site characterization.

II. SYNTHESIS OF REVIEW COMMENTS AND RESOLUTION MEETINGS

A. SOURCES OF INFORMATION

The formal procedures used in reviewing the manuscript required each reviewer to use Document Review Sheet forms for recording his or her comments, referenced to specific pages in the manuscript. Copies of these were then supplied to the author, and it was the author's responsibility to resolve any disputes with the reviewer(s). This review resulted in a rather large volume of comments from about two dozen Project scientists, representing many technical specialties. These comments were commonly quite detailed, sometimes redundant, sometimes contentious toward the author, and in some cases the reviewers differed in their perspective as to changes that were recommended. To expedite the review process, a series of comment resolution meetings was held to allow the author and principal reviewers to clarify their arguments and attempt to reach agreement. In the course of these meetings, it became obvious that not all the reviewers' technical objections could be satisfied, and that some of the disagreements resulted from the reviewers not understanding what the author meant. The following sections of this review report are intended to summarize the technical areas of agreement and disagreement between the author and the reviewers, and to point out stylistic problems that are sufficiently serious to impede understanding of the author's ideas, both within and outside the Project. In writing these sections, the editors have relied on the written comments, resolution meetings, and subsequent discussions with the author, some of the reviewers, and other colleagues. The editors hope that this has produced an accurate synopsis of the entire review process.

The original Document Review forms, along with the unpublished draft manuscript, are part of the public record and are archived by the Yucca Mountain Project Office.

B. HYDROGEOLOGIC FRAMEWORK

The manuscript fails to adequately consider the importance of geologic conditions in defining the framework for groundwater flow. The importance of geologic factors has been emphasized in numerous reports by federal, state, academic, and private investigators during the past several decades. Decisions on the allocation of water rights, development of water supplies, environmental impacts of water development, and the siting of underground nuclear test areas, among others, have been heavily influenced by this understanding. It does not necessarily follow that this traditional wisdom is entirely correct. However, demonstration that active tectonic processes are dominant, or even significant, factors requires that the known or probable hydraulic influences of the existing geologic framework first be accounted for in the analysis.

The geologic framework of the groundwater sub-basins addressed in the manuscript is characterized by a great variety of rock types, resulting in a wide range of primary hydraulic properties. Several periods of tectonic deformation have produced major structural features that have modified the original depositional positions of stratigraphic units and have caused extensive fracturing of the rock mass. Overthrusting and extensional faulting have, in places, formed preferential pathways for groundwater flow and, in other places, have created flow barriers by disrupting the continuity of geologic units, and by the formation of fault gouge.

Geochemical processes have further changed rock properties. The dominant regional aquifer, a sequence of Upper Cambrian through Devonian carbonate rocks (termed the lower carbonate aquifer by Winograd and Thordarson (1975)), probably contains karstic solution channeling along bedding planes, fractures, and faults that results in extremely high transmissivities in places. The volcanics have, in places, also been pervasively altered by argillation and zeolitization, reducing both matrix and fracture permeability. Fractures in all rock types contain depositional mineral fillings at various locations and depths, contributing particularly to the low permeability of rocks older than the lower carbonate aquifer and probably also of the deeper volcanic rocks.

The resulting variability of the hydrogeology has been recognized and described in the many scientific reports dealing with the northeastern Death Valley groundwater subbasins. (See, for example, Winograd and Thordarson (1968, 1975), Blankennagel and Weir (1973), Sinnock (1982), Waddell (1982), Czarnecki and Waddell (1984), Waddell et al. (1984), and Robinson (1985).

1. HYDRAULIC PROPERTIES

The hydrogeologic framework is discussed briefly on Page 4-2 of the manuscript with the assertion that its intrinsic complexity is so great that it cannot be effectively characterized nor realistically simulated in models. The conclusion is reached that the Tertiary and older rocks should be treated as a single hydrogeologic unit. This conclusion is carried forward as an assumption that pervades interpretations of field data in subsequent parts of the manuscript.

Several reviewers considered the treatment of the suballuvial rock mass as an undifferentiated unit to be an unwarranted, seriously unrealistic assumption. In effect, it precludes consideration of the spatial distribution of effective permeability, which ranges over several orders of magnitude, in explaining hydrologic observations. It leads directly to later suppositions that hydraulic and thermal perturbations necessarily reveal differences in the state of in situ stress or in heat flow into the base of the geohydrosphere.

The manuscript considers variations of porosity only as they may affect the mechanisms of flow, i.e., whether flow occurs principally through matrix interstices or through fractures. The role of matrix or interstitial porosity in contributing to the storage characteristics of the rocks is ignored; storativity of the rock mass is attributed only to the fracture systems. Although this may be a reasonable assumption for analyzing the effects of short-term disturbances of hydraulic potential in the majority of the rock mass, local lithologic characteristics may render the assumption inappropriate. More importantly, the manuscript addresses principally hydraulic responses to tectonic stresses that change over geologic time frames. For such slowly changing stresses, matrix storativity may dominate that of the rock mass despite the fact that matrix permeability is commonly several orders of magnitude less than effective fracture permeability. The effect would be to damp out changes of fluid pressure resulting from changes of effective stress. For more rapid changes of stress, such as would accompany faulting, the effect of matrix hydraulic diffusivity would lag behind that of fracture diffusivity, not affecting the maximum pressure change but possibly extending the duration of the disturbance.

Traditional hydrogeology holds that rocks in general become less permeable with depth as pores and fractures close due to the growth of secondary minerals and to the weight of the overburden. At depths determined by the geochemical environment and the mechanical properties of the rocks, the geohydrologic system can be considered, for practical hydrologic purposes, to have a closed boundary that does not permit appreciable fluid to enter or leave the system. In those parts of the region around Yucca Mountain that are underlain by the Paleozoic carbonate rocks, the base of the hydrosphere is assumed by many to coincide effectively with the base of the lower carbonate aquifer. In areas where the volcanics are very thick, the base of active flow has not been determined, but significant permeability is present at a depth of about 3 km in one test hole on Pahute Mesa (Blankennagel and Weir, 1973; Sass and Lachenbruch, 1982). In contrast, the model proposed in the manuscript considers the depth of the effective base of the geohydrosphere to vary in time according to the transient state of stress. Further, it considers the hydrologic system immediately above this base to be significantly influenced by heterogeneous heat flow resulting from relatively local upwelling of the mantle into the crust.

2. TECTONIC MODELS

The manuscript states on Page 3-7 that, "for purposes of ... hydrologic considerations, it is not of great importance to know which tectonic model provides the best explanation for the observed structural arrangements and kinematic movement..." Several reviewers take exception to this statement. First, the "structural arrangements," which strongly influence the spatial distribution of hydraulic properties within the rock mass, cannot be fully observed; rather, they must be inferred to a great degree from an understanding of their origin. Second, the temporal behavior of the stress field and resulting hydraulic response would differ significantly among the various models being considered. This topic is addressed in greater detail in Section II.C of this review.

Project hydrologists (and others) have recognized that fractures and faults that trend approximately in the direction of the greater horizontal stress may be less tightly closed than those that trend in the direction of the least stress. However, within the short time period of existing observations, the effect has been considered to be constant and accounted for in the invariant anisotropy. Furthermore, in the vicinity of the Nevada Test Site, the structural grain and the fundamental flow direction dictated by the geographic positions of recharge and discharge areas are from the north-northeast to south-southwest. Because this is also the approximate trend of the greater horizontal stress, the effects could not be separated unless the orientation or magnitude of the stress field were to change significantly. In the absence of opportunity to observe future changes, understanding of the correct tectonic model, or the set of most likely models, is required in order to make credible estimates of the hydrologic effects of possible future tectonism.

3. SATURATION AND WATER-TABLE DEFINITION

The manuscript discusses saturation of the rock matrix in relation to the position of the water table in Section 4.3, Page 4-9, with reference to Plate 4.3-1. The data are drawn from two reports that merely present results of laboratory determinations of various physical and hydraulic properties, including the degree of saturation, along with other data recorded during the drilling and testing of two holes (UE25b-1 and USW H-1) that were completed during the early stages of Yucca Mountain exploration. The conclusion is reached in the manuscript that "the water table seems to be a plane below which most fractures contain water, but the rock matrix is not fully saturated. Above this plane, however, either none or only some fractures contain water. Nevertheless, the degree of matrix saturation is relatively high." Although it is not stated explicitly, the conclusion leads to the supposition that the position of the water table is related only to hydraulic characteristics of the fractures, which is the position taken in development of the conceptual model in Section 3 of the manuscript.

The manuscript does not acknowledge that the reports from which the data were drawn lacked any discussion or interpretation of the saturation data. However, both of these reports were followed by interpretive analyses of the hydrologic data from these boreholes (Lahoud et al., 1984; Rush et al., 1984) with discussions of the probable drying of the samples; borehole testing data from these later reports are referenced elsewhere in the manuscript. Laboratory determinations of degree of saturation are very sensitive to preservation of in situ conditions during sampling and during sample handling, storage, and analysis. As noted above, holes UE25b-1 and USW H-1 were drilled early in the exploratory program, in fact at a time when the possible host units for repository development were considered to be deeper tuffs beneath the water table, and saturation was therefore assumed. Saturation data for unpreserved core is not a primary hydrologic data need for samples obtained below the water table. However, it is commonly included in laboratory reports for such purposes as checking the consistency of "as-received" and saturated bulk density.

4. REGIONAL WATER-TABLE CONFIGURATION

Section 4.3 of the manuscript goes on to discuss the significance of the configuration of the water table in regionally important aquifers. The discussion builds upon the premise established in Section 3 of the manuscript that the vertical positions and lateral gradients of the water table reflect the state of stress in the rock mass and its influence on fracture apertures. A bias toward demonstrating the validity of the premise is established by denying the significance of spatial variations in hydraulic properties of the rock mass and by implying temporal instability of the water table from a limited and selective set of matrix-saturation data of questionable relevance.

According to the manuscript (Page 4-10), the configuration "reveals that features expected to be present in a tectonically controlled flow field are also present in this system. Configuration of the water table includes: a) steep slopes; b) hydraulic 'plateaus' where horizontal gradients of hydraulic potentials are small; c) hydraulic mounds; and d) hydraulic sinks." It is recognized in the manuscript that the features do not provide unambiguous proof of tectonic control of the water table, citing "narrow groundwater barriers" (i.e., faults) as an alternative cause of the "plateau-step-plateau" characteristic and "man actions" (pumping or injection) as alternative causes for hydraulic sinks and mounds. There are many other reasons for irregularity of the water table or deeper potentiometric surfaces, some of which are discussed below and in several subsequent sections of this review.

Most groundwater recharge in the region occurs in the high mountains and mesas that receive annual averages of more than 8 to 10 inches of precipitation, occurring mostly as winter snowfall, or in ephemeral channels that carry run-off to the permeable alluvium that borders these highlands (Winograd and Thordarson, 1975; Claassen, 1985). The principal recharge areas that provide the driving potential for groundwater flow in the vicinity of the Nevada Test Site and Yucca Mountain include Pahute Mesa, the Belted Range, and the Spring Mountains. Groundwater beneath Yucca Mountain flows southward to discharge by evapotranspiration at Alkali Flat (Franklin Lake Playa) in the southern Amargosa Desert and possibly, in part, at springs in Death Valley. Other subbasins of the groundwater system discharge to the east and west in the areas of Ash Meadows and Oasis Valley, respectively. The Ash Meadows groundwater system also derives recharge from a vast area to the east and northeast. Consequently, flow converges from a broad geographic distribution of recharge areas to a few closely grouped and very small discharge areas. Complexities resulting from the structural dislocations of the pre-Tertiary rocks cause more local convergence and divergence of flow, whether to avoid elevated rock masses of low permeability or to take advantage of permeable pathways, such as may be provided by faults (Winograd and Thordarson, 1968; 1975). Similar hydrogeologic variability occurs in the volcanic rocks because of the variety of depositional conditions and subsequent alteration and faulting that accompany the evolution of caldera complexes.

The regional significance of areas of relatively low gradients ("hydraulic plateaus") separated by zones of steeper gradients was addressed by several reviewers. The surface shown on Plates 4.3-2, 4.3-3, and 4.3-4 is an interpretive representation of the potentiometric surface in regionally significant aquifers. Over large areas, particularly those underlain by the lower carbonate aquifer, the surface does not coincide with the water table. The regional potentiometric surface is generally lower than the local water table in areas where the regional aquifers are gaining flow by downward recharge through overlying rocks; it is higher where the lower carbonate aquifer loses flow by upward discharge into overlying rocks and alluvium, principally in the Amargosa Desert.

Rather than being "remarkable," as stated on Page 4-9 of the manuscript, the potentiometric surface merely reflects the topographic, climatic, lithologic, and structural variability of the region. In fact, these factors, particularly lithology and structure, are major considerations in interpolating between sparse data points in the preparation of a potentiometric map. The interpolation is based on the hydrologic principles that the lateral gradient is approximately proportional to the degree of convergence required by the flow system geometry and to the flux (volumetric rate of flow) of water, and that it is inversely proportional to transmissivity (permeability times thickness) of the water-transmitting section. The qualifier "approximately" is used to recognize that actual flow paths are lateral only in the average sense and that anisotropy of transmissivity may either enhance or impede the tendency of water to flow along the most direct pathways from sources to discharge areas. In reality, flow occurs along pathways that offer the least overall hydraulic resistance. In an area of hydrogeologic complexity, both lateral and vertical local flow directions accommodate the spatial and directional variations of permeability while concurrently satisfying the requirement to deliver water from source areas to discharge areas. Because permeability ranges over several orders of magnitude for the rocks in this region, and because the flow systems converge from broad recharge areas to small areas of discharge, the areal distribution of the average potentiometric gradient is expected to be irregular even if the sources of variability noted above are time-invariant. However, it is possible that there are effects, as-yet unquantified, of coupling between tectonic processes and hydrology.

The "notable feature," or abrupt southeastward gradient of the regional potentiometric surface, extending from south of Beatty northeastward across Yucca Mountain and Yucca Flat has hydrogeologic significance, as is discussed by Winograd and Thordarson (1975). To the northwest of the lineation, the flow system is developed principally in thick volcanic rocks of low to moderate transmissivity. On the west side of Yucca Flat, the eastward extent of poorly permeable rocks is extended by a thrust plate that brings the upper clastic aquitard (Devonian-to-Mississippian Eleana Formation) to the surface. North of Yucca Flat the volcanics thin or are absent over a structurally elevated block of the lower clastic aquitard, a sequence of Upper Precambrian and Lower Cambrian quartzites and shales of low transmissivity. To the southeast of the potentiometric lineation, the lower carbonate aquifer is down-faulted and occurs beneath the water table. Its high transmissivity and continuity along the flow path combine with the relatively small groundwater flux to produce a small potentiometric gradient from the approximate latitude of northern Yucca Flat to discharge areas in the Amargosa Desert. In effect, the lower carbonate aquifer serves as a highly permeable underdrain and sidedrain for the region that is north and northeast of Mercury. Further downgradient (i.e., to the south), the aquifer serves as an almost equipotential source of head which is higher than that represented by the water table in the overlying alluvium and tuffs.

On the downgradient side from Jackass Flats to Beatty, high transmissivity is afforded by very thick alluvium and, in places (e.g., at wells J-12 and J-13), by fractured welded tuffs. By taking these considerations into account, groundwater flow models (Waddell, 1982; Czarnecki and Waddell, 1984) can reproduce the potentiometry observed, but the actual cause of the large gradient is unknown. On the upgradient side, the hydrogeology is not yet well characterized. The actual position and sharpness of the gradient is moderately well constrained at Yucca Mountain itself but, over most of its length, it is an artifact of the transmissivities assigned by parameter-estimation techniques during modeling (Czarnecki and Waddell, 1984) -- i.e., hydrogeologic control was assumed.

Interpretations that attribute the irregularity of the potentiometric surface to patterns of tectonic stress and heat flow, such as are expressed in the manuscript, cannot be given credence unless the demonstrated hydrogeologic factors are first accounted for. In the opinions of most reviewers, the residual irregularities, those that cannot be explained by known or reasonably anticipated hydrogeologic considerations, do not exist at significant magnitudes. The Project is certainly obligated (as expressed in the SCP) to develop an understanding of the cause or causes for the large gradients near Yucca Mountain. With respect to more distant areas, such as the Bullfrog Hills and the Greenwater Range, reviewers have not reached a consensus as to the importance of establishing high confidence in the causes for occurrences of water at relatively high altitudes.

C. TECTONIC AND GEOTHERMAL FRAMEWORK

It is proposed in the manuscript that heterogeneous heat flow and deformation resulting from mantle dynamics may be responsible for the configuration of the present water table and may also produce large episodic fluctuations of the water table (Pages 3-25 and 3-27). Although the structure and stratigraphy of the area are complex, the author postulates that fracturing in the system is so pervasive and deformable that thermal processes and in situ stress dominate in determining the configuration of the water table and the deeper distribution of hydraulic potential (Pages 3-13 and 4-9). The reviewers noted that particular attention must be paid to the scale of these phenomena when comparisons are made. The scales of heat-flow variations and deformational features resulting from mantle dynamics are thought to be much larger than the scale of variations in the water table shown on Plates 4.3-2 to 4.3-6. Instead, the configuration of the water table is more directly comparable to the scale of features related to variation of hydrologic properties such as vertical and horizontal lithologic variation, individual faults, faulting domains, caldera structures, topography, and other local durable features of the geology of the area. The manuscript does not appear to account satisfactorily for the significant effects that these local tectonic and stratigraphic features have on groundwater flow.

The author does not attempt to demonstrate that the proposed fluctuations in the water table actually occur in extensional tectonic settings. If the hypothesis is valid, the Rio Grande rift (which the reviewers presume the author has offered as an analog to the Yucca Mountain region) and other rift zones would be expected to exhibit the type of hydrologic behavior described in the manuscript. Because of their higher heat fluxes and deformation rates in comparison to the southern Great Basin, tectonically and thermally driven water table fluctuations should be more readily observable in these settings than at Yucca Mountain. However, no examples of the proposed phenomenon are mentioned in the manuscript. Therefore, the author proposes, on theoretical grounds, a phenomenon that is not demonstrated to exist.

1. MANTLE UPWELLING AND RIFT STRUCTURE

Section 3.0 of the manuscript begins with a discussion of a model of the Rio Grande rift. The initial discussion does not explicitly state why this model is presented, but it implies that processes operating in the Rio Grande rift are generally applicable to extensional processes that occur in the entire Basin and Range province, including Yucca Mountain. Subsequently, on pages 3-21 and 3-22, it is postulated that a zone of mantle upwelling exists in the vicinity of the site that is analogous to the Rio Grande rift and other incipient or active rift zones. It is further suggested that this mantle upwelling produces thermal anomalies in the crust that provide one of the driving forces for the intermittent mounding of the water table hypothesized. The geochemistry of basalts in the Yucca Mountain region and local variations in heat flow and teleseismic P-wave residuals are cited as evidence for active mantle convection at the site.

a. **Applicability of the Rio Grande Rift Model**

The Rio Grande rift is similar to Yucca Mountain in that it has silicic volcanic rocks (including silicic tuffs), calderas, and basaltic volcanism. However, the Rio Grande rift's magnetic and gravity signature, the volume of basalt extrusion, the heat flow, the structure and thickness of the crust, and the scale of the area (see Riecker, 1979) are all different from those of the southern Great Basin. The contrasts in these characteristics reflect the fundamentally different tectonic regimes of the two provinces, both of which happen to be extensional. It has been proposed that the Rio Grande rift represents a long, linear (>600 km) asthenospheric upwelling through relatively thick crust (45 km), which has thinned in the area of the rift to 33 km (Chapin, 1971; Olsen et al., 1979). In contrast, the Great Basin Province is a broad regional area (>600 km in diameter) of more extreme crustal thinning. The two areas are of vastly different scales and crustal configurations. They share a common extensional origin but the rates and magnitudes of tectonic and asthenospheric processes occurring in the two areas are significantly different.

Observed temperature fields and calculated heat fluxes in the Rio Grande rift range to much higher values than have been observed in the Great Basin. The average heat flux in the Great Basin is about 2 HFU, with a reported maximum of 3.8 HFU in the Battle Mountain high of north-central Nevada (Sass et al., 1971). Heat flow in the southern Great Basin is less, with large areas (including Yucca Mountain) averaging less than 1.5 HFU (Sass et al., 1971, 1988). The average in the Rio Grande rift is about 2.5 HFU, and values as high as 9.7 HFU are reported (Reiter et al., 1979). The high heat flow in the Rio Grande rift is more manifest when one considers its crustal thickness of about 33 km (Olsen et al., 1979), in contrast to the Great Basin crustal thickness of approximately 20 km or less.

The reviewers felt that the discussion of asthenospheric upwelling on Page 3-1 was unconvincing, that the reference cited was not representative of the current understanding of the geophysics of the rift, and that the discussion of Plate 3.1-1 does not clearly state or support the author's points. The general description of the rifting process in "extension dominated tectonic environments" and the suggestion that extension in the Great Basin region is the result of "outward flow in the upper mantle" (Page 3-2) are likewise not well supported by references or explanation.

The author proposes that there is a close correlation between areas with low crustal P-wave velocity and areas with large geothermal gradients, citing the Rio Grande rift as an example (Page 3-21). Discussion of the seismic and thermal data of Bridwell and Potzick (1981) for the Rio Grande rift, in support of the claimed correlation, appeared to reviewers to be overly generalized and inaccurate. Examination of Plate 3.3.1-5 reveals the following:

1. As depicted by Bridwell and Potzick (1981), there is a significant decrease in the depth of the Moho from 40 to 30 km beneath the rift zone and its flanking provinces, the Nacimiento Mountains and the Sangre de Cristo Mountains. Above the raised Moho, the seismic velocities of both the lower crust and the upper crust are lower than in regions to the west (Colorado Plateau) and east (Great Plains).

2. The structure of the heat flow anomaly is more complex than the author's description, with lower heat flow (as low as 1.8 HFU) in the central part, including the eastern Rio Grande rift and western Sangre de Cristo Mountains, flanked by indications of significantly higher heat flow. This complexity is not exhibited by the rather limited seismic data. In the Colorado Plateau to the west of the thinned, low-velocity crust (see Plate 3.3.1-5), there is another positive heat-flow anomaly of 2.4 HFU. Seismic data are lacking directly beneath this anomaly.

The density of the seismic data presented by Bridwell and Potzick (1981) is, in fact, insufficient to prove or disprove the claimed correlation of seismic and thermal parameters. Nonetheless, the known characteristics of the Rio Grande rift are much more complex than represented in the manuscript, and upon closer inspection may bear little more than qualitative resemblance to observed conditions in the vicinity of Yucca Mountain. The Rio Grande rift and the Yucca Mountain area may both be extensional, but they are not demonstrated from examining presently available data to be analogous with respect to crustal and upper mantle processes.

b. **Southern Great Basin**

The author concludes that the teleseismic P-wave data for depths of 0 to 15 km of Monfort and Evans (1982) indicate that changes in the seismic structure of the upper crust in the vicinity of Yucca Mountain can be attributed to thermally induced alterations in viscosity and rigidity caused by mantle upwelling (Pages 3-20, 3-21, 3-29, and 4-13). These conclusions are based on claimed correlations of P-wave anomalies with zones of basaltic volcanism and with variations in heat flow. Several reviewers questioned the validity of these correlations and the conclusions drawn from them.

i. **P-Wave Residuals and Volcanism**

The manuscript proposes a "remarkable correlation" between the location of a low velocity trough on Plate 3.3.1-1 and the location of Pliocene and Quaternary volcanic centers on Plate 3.3.1-2 (Pages 3-21 and 3-29). A close comparison of these two plates at the same scale indicates the proposed correlation is unconvincing. The Death Valley - Pancake Range volcanic zone and the trend of the trough of low P-wave velocity intersect near the southwest corner of the Nevada Test Site and diverge at an angle of about 20 degrees. Hence, the two areas with the greatest concentrations of Pliocene and Quaternary volcanism (the Lunar Crater and southern Death Valley volcanic fields) are actually located outside the low velocity zone in areas of slight positive anomalies.

One of the low-velocity anomalies referred to in the manuscript (Page 3-20) occurs at Pahute Mesa, closely following the limits of the Silent Canyon - Timber Mountain caldera complex. The accumulated thickness of volcanic rocks within these calderas is very large and dominated by tuffs having low density, relatively high compressibility, and low seismic velocity. The volcanic section at Pahute Mesa has been determined from exploratory drilling to be (at least locally) more than 4,000 m. thick (Blankennagel and Weir, 1973). The average seismic velocity in tuff is believed to be somewhat lower than in Paleozoic sediments and igneous rocks that occur below the tuffs. The velocity anomaly is readily explained as the result of local variations in thickness of the Tertiary volcanic section, if this section were to have 20 percent (1 km/s) lower velocity than the underlying rocks. This explanation is based on directly observable quantities and was believed by the reviewers to be more plausible than one invoking processes of mantle intrusion into the crust, heat flow from the mantle, concentrated crustal heat generation, and relict temperature anomalies. The area of the Skull Mountain - Wahmonie anomaly, discussed in the manuscript on Page 3-20, also has a thick tuff sequence and, in its central and western parts, large thicknesses of alluvium as well. Consequently, this anomaly may be attributable to the thickness of low-velocity materials in the uppermost crust.

The reviewers noted that there is no indication on the maps of Monfort and Evans (1982) that the observed shallow anomalies persist to greater depths (i.e., 15-31 km, 31-81 km, 81-131 km, 131-231 km). If the anomalies were related to mantle upwelling they should also be observed in these intervals.

ii. P-Wave Residuals, Heat Flow, and Temperature

The author proposes (Pages 4-19 and 4-20) that increased heat flow and relatively high subsurface temperature (at a reference depth of 500 m) are clearly associated with low-velocity anomalies in the southwestern Nevada Test Site and Pahute Mesa areas. A map combining the velocity and temperature data was prepared by the reviewers as a visual test of the proposed correlation (Figure II.C-1). This map shows contours of the teleseismic P-wave departures (in percent) from the regional average arrival times, visually transferred from Plate 3.3.1-1 to the larger scale of Plate 4.6.2-1. The reviewers recognize that the contour map by Monfort and Evans (1982) is based on limited control, and that the scale of phenomena for residuals and heat flow may involve different regions of the crust. In spite of these problems, we continue in order to evaluate the author's conclusions.

The borehole data show calculated heat flow values and temperatures at a constant depth of 500 m below the surface. For holes in which temperatures were not actually measured at the 500-m depth, they were extrapolated from the logged intervals. The Pahute Mesa holes were re-plotted from Blankennagel and Weir (1973), as Sass and Lachenbruch (1982) had plotted them about 7 km north of their actual locations. The southward translation tends to strengthen rather than weaken the author's proposed correlation.

The manuscript (Page 3-21) associates the relatively higher heat flow values in the exploratory borehole UE25a-3 and wells TW3, TW4, TW5 and TWF with the negative velocity residual anomaly located in the southwestern corner of the Nevada Test Site. Inspection of Figure II.C-1 clearly shows that four of these holes are located across the zero contour (i.e., the locus of regionally average P-wave velocity) in the area of greater velocity. Holes TW3 and TW4 (both 2.2 HFU) are located on or across the +2 percent velocity residual contour line. The greatest heat flow (3.1 HFU at UE25a-3) that has been reported in southern Nevada (Sass et al., 1980; Sass and Lachenbruch, 1982;

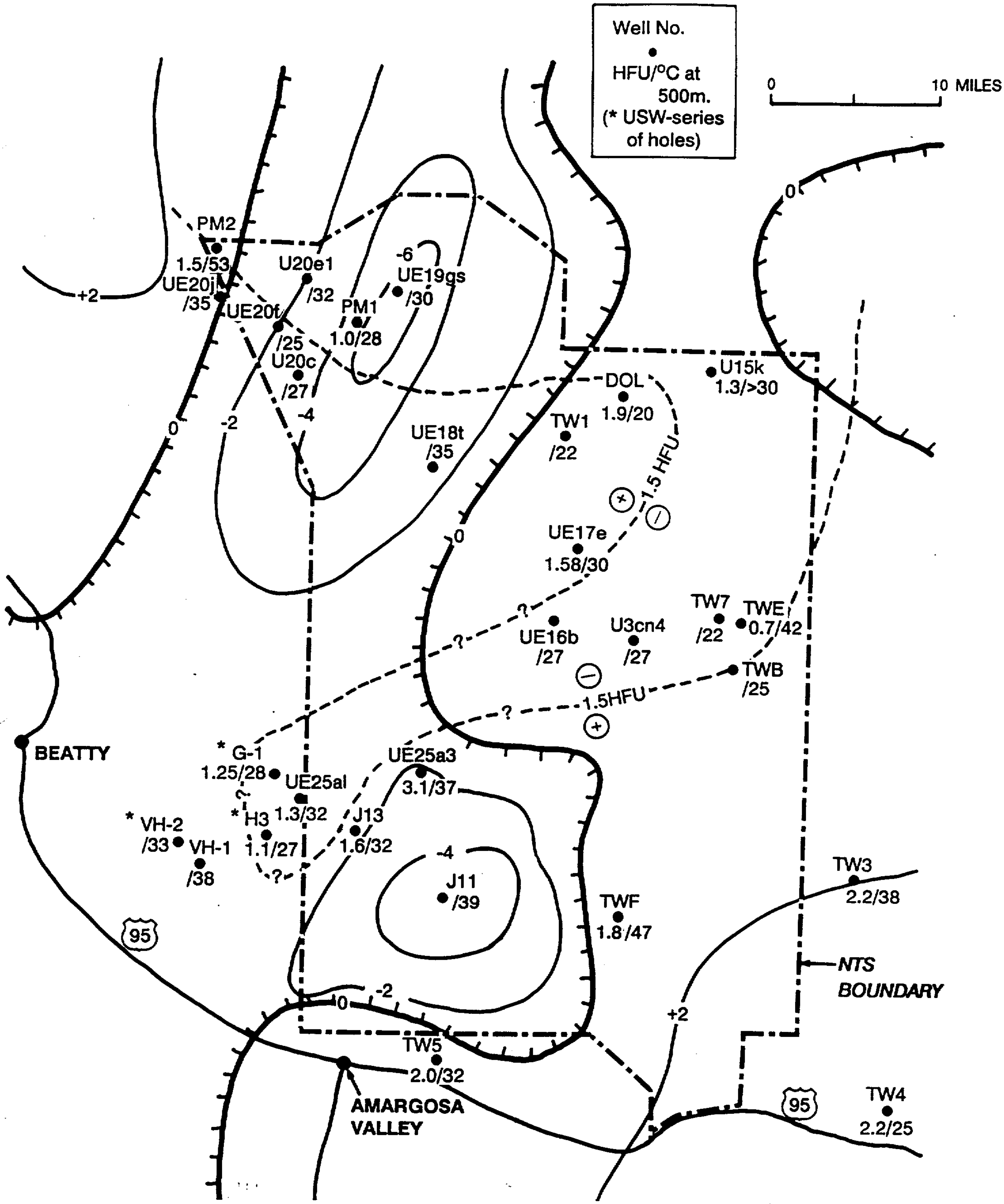

Figure II.C-1. Seismic-velocity anomalies in the vicinity of the Nevada Test Site, compared with data on heat flow and approximate temperatures at a depth of 500 m. Adapted from Monfort and Evans, 1982; Sass and Lachenbruch, 1982; and Sass et al., 1988. Solid lines are seismic p-wave residuals (as percentage departure from the regional average); dashed lines are heat flux contours (1HFU = 42mw/m^2).

Sass et al., 1988) does occur within the seismic anomaly of southwestern Nevada Test Site. Nonetheless, of the eight sites for which the calculated heat flow equals or exceeds the median value of 1.6 HFU, only two (Well J-11 and UE25a-3) are within the low velocity residual anomaly. The difference in the number of sites with above-median heat flow may suggest a correlation that is inverse to that claimed by the author. However, the average heat flow for the six holes within the anomaly Figure II.C-1 is 1.56 HFU, whereas, for the nine holes in areas with a positive P-wave velocity anomaly, the average is 1.69 HFU. This small difference may not be statistically significant.

The manuscript (Page 4-19) proposes that the in situ temperatures at a constant depth of 500 m also indicate a "very revealing" correlation with the seismic velocity data and that convective flow systems are shown to be present. Specifically, the manuscript states that in situ temperatures are noticeably higher in the low velocity area west of the zero-departure contour line and are low in the area of higher velocities east of the zero contour. It is also stated that the low velocity anomalies at Pahute Mesa and in the southwestern corner of the Nevada Test Site "are clearly reflected in the pattern of spatial distribution of thermal inhomogeneities." These statements are not supported by the data shown on Figure II.C-1. Some of the warmest temperatures (38 to 47°C) are located east of the zero contour at boreholes TWF, TWE, and TW3. Within the low velocity area, the boreholes at Yucca Mountain (UE25a-1, USW G-1, USW H-3) and at Pahute Mesa (PM-1, UE19gs, UE20c, U20e-1, UE20f) are relatively cool (25 to 32°C). The highest temperature in the area (borehole PM-2) at 500 m (53°C) is located west of the low velocity anomaly at Pahute Mesa in an area of slightly positive velocity residuals. Two holes having relatively high temperatures (Well J-11 and UE25a-3) are within the low velocity area in the southwestern part of the Nevada Test Site, but a higher temperature value (Well TWF) is located to the east of the velocity low and slightly east of the zero contour. As was the case with respect to heat flow, the subsurface temperatures do not display a significant difference. The average for the 14 boreholes within the low-velocity anomaly is 31.6°C, and that for the 15 others (including PM-2 and UE20j) is 31.7°C.

Sass et al. (1988) tentatively extended the area of low heat flow (<1.5 HFU) that occurs at Pahute Mesa and Yucca Flat southwestward to Yucca Mountain. Because data are lacking, the narrow extension is tenuous at best, and Yucca Mountain may in fact be an isolated area of low surface heat flow. In either case, however, the correlation of seismic and thermal anomalies that is claimed so positively in the manuscript is strongly contradicted by the existing data.

iii. **Basalt Geochemistry and Rifting**

The author proposes that the geochemistry of the basalts in the Death Valley - Pancake Range zone also are indicative of a convective flow system in the mantle and that the "ascending limb" of this system is responsible for the observed basaltic activity. He then concludes (Page 3-29) that the geochemistry of the basalts and the inferred thermal origin of the teleseismic P-wave anomalies indicate the presence of an immature rift structure along the Death Valley - Pancake Range zone.

Reviewers did not agree that the geochemistry of the basalts of the Death Valley - Pancake Range volcanic zone, which indicates melting of an incompatible-element enriched mantle, supports an interpretation of convective upwelling of mantle into the crust. As cited in the manuscript, Semken (1984) did interpret the data as indicating small scale convective mixing of the mantle and lower crust under the southern Great Basin. That hypothesis is not, however, a unique explanation of the data and, even if it is true, it falls far short of being a convincing basis for some of the author's inferences from that data, such as the "presence of a second, ascending limb" of convective flow in the mantle under Yucca Mountain.

New data (Farmer et al., 1989) indicate that the basalts, which have been erupted discontinuously over the past 10 m.y. in southern Nevada, were derived from a single, nearly uniform mantle source that is isotopically distinct from asthenospheric mantle. The process that produced the unusual isotopic signature of the subcontinental mantle in this region is, therefore, one that occurred more than 10 m.y. ago. Moreover, because the unusual isotopic signature of the basalts reflects preservation of a long-lived, chemically distinct subcontinental mantle source, it is evidence that any mantle upwelling under this area is not displacing or causing large-scale mixing in the lithosphere. Rather than being support for the type of vigorous, focused upwelling of asthenospheric mantle that occurs under rift zones, as is implied by the author, the isotopic signature of these basalts is evidence against it.

The reviewers agree that the mantle of the earth does convect and that, in an area of extension such as the Basin-and-Range province, upwelling in the mantle would seem to be required by the principle of conservation of mass. Basaltic volcanism in southern Nevada over the last 10 m.y. may well be related to some pattern of upwelling in the mantle. In the broadest sense, rifting may be considered synonymous with extension and there is no disagreement that southern Nevada is an area of extension. There is, however, no evidence of a rift zone in southern Nevada in the sense that that term is used in describing the Rio Grande rift, for instance. There appears to be no current seismicity, crustal velocity or curie-isotherm anomaly, or structural context to support the interpretation of an incipient rift.

2. GEOTHERMAL FRAMEWORK OF YUCCA MOUNTAIN

Although seismic and basalt-geochemistry data reveal little about the geothermal framework of the Nevada Test Site and Yucca Mountain area, borehole temperature measurements and calculated heat fluxes show that the Great Basin, with an average flux of about 2 HFU and values exceeding 3 HFU, has greater heat flow than the continental average (Sass et al., 1971). Furthermore, the relatively numerous determinations of conductive heat flow to depths of a kilometer or more in the southern Great Basin do support the author's observation that the geothermal pattern is quite irregular, though not necessarily his interpretation of the cause.

a. **Heat Flow Determinations**

Most of the heat-flow estimates considered in this discussion have been made by Sass and his colleagues using the direct technique of multiplying rock thermal conductivity by the geothermal gradient, which was measured by borehole logging. The temperature logging technique is well calibrated and is not a source of significant error. Thermal conductivity, however, cannot be measured continuously through the depth range of interest. Rather, it is measured in the laboratory (Sass et al., 1971, 1984) on a limited number of core samples obtained from discrete depths in some, but not all, boreholes. In the intervals between samples and at unsampled locations, thermal conductivity must be estimated based on formation or rock-type averages, or on P-wave velocity logs. Based on data for tuffs at Yucca Mountain presented by Sass et al. (1988), errors for individual estimates should not exceed ±20 percent, with a more likely error of ±10 percent, and possibly with a small systematic bias. This suggests that errors associated with thermal conductivity in the estimates of conductive heat flow should be less than about ±0.2 HFU.

Much more significant errors may arise from disruption of the natural hydrologic system by using a borehole that is not completed with grouted casing. Uncased or ungrouted boreholes allow movement of water between zones of different potential. Most of the temperature logs obtained from the vicinity of the Nevada Test Site demonstrate borehole flow in response to vertical differences of hydraulic potential; in fact, they have long been used to identify permeable zones, which commonly are zones of either inflow to or outflow from the hole (Blankennagel, 1967, 1968; Blankennagel and Weir, 1973). This effect distorts conductive thermal gradients in many holes and is a source of uncertainty in many others. Where borehole flow appears to be minor, a gradient is commonly calculated by a least-squares linear fit to the data and should be reliable if no-flow intervals occur both above and below the perturbation. An alternative is to select shorter segments of the profile that are most likely to be no-flow zones, such as a linear segment in the deepest part of the hole, or segments shown by flow surveys to be unperturbed. Sass et al. (1988) compared heat-flow estimates for gradients determined by the least-squares and deep-segment methods for nine holes at Yucca Mountain. Three of the nine (USW G-1, USW H-1, and USW H-3) gave comparable results; for the others, the deep-segment method yielded larger gradients and greater estimated heat flows by 1/4 to 1 HFU. This analysis does not preclude the possibility that the least-squares gradients indicate undisturbed rock temperatures above the zones used for the deep-segment estimates; conductive heat flow might actually decrease upward in the sections. Alternatively, the results may indicate that the undisturbed, conductive thermal gradients in the rock were masked by flow in the boreholes. Poor thermal coupling of the fluid in the casing, or in additional measurement tubing, with the rock may also suppress irregularities of the thermal profile, whether they are natural or result from intra-annular flow between uncemented casing and the rock.

Finally, direct heat-flow calculations necessarily reflect only heat flow by conduction in the rock. Sass et al., (1971) recognized the probability of decoupling conductive heat flow by groundwater flow. The author includes this hydroconvective component of heat movement within his use of the term "thermal conductivity," leading to confusion by the reviewers until this was clarified in a comment-resolution meeting. A fundamental difference between reviewers and the author is whether recharge-driven groundwater flow is responsible for much of the variability in calculated heat flows (perhaps as much as 1.5 HFU) and temperatures in the shallow crust, or whether the basic variability derives from variable heat input to the base of the flow system, providing an important part of the potential field that causes groundwater flow.

b. **The Eureka Low**

The "Eureka Low" was defined by Sass et al., (1971) as a broad area extending from Eureka, Nevada, southward to about the northern border of the Nevada Test Site, within which heat flow is characteristically less than 1.5 HFU. In contrast to the statement in the manuscript (Page 4-20) that "The anomaly was attributed to a complex hydrologic disturbance of an unspecified nature," Sass et al. (1971) offered two specific alternative explanations: "It could represent a systematic hydrologic effect of regional extent or it might be a region where temperatures in the lower crust and upper mantle have been below the solidus for some time. However, the abrupt transitions on the margin of the feature ... favor a fairly shallow origin for the anomaly. Our fragmentary temperature data from very deep holes in southern Nevada suggest an explanation in terms of systematic though complex interbasin groundwater flow with appreciable vertical velocity components to depths of about 3 km..." Blackwell (1978) related the Eureka Low to a crustal region where older volcanism has occurred, in comparison with the Battle Mountain high where more recent volcanism has occurred. Sass et al., (1971) also stated, "...it seems reasonable to interpret the Battle Mountain high as a transient effect of fairly recent crustal intrusion."

Although Sass and Lachenbruch (1982), on their heat-flow map of the western United States (Plate 4.6.3-3 in the manuscript under review), did not formally extend the Eureka Low into the Nevada Test Site, which is contiguous on the south to the regional anomaly, they state (Page 7), "Beneath Pahute Mesa..., temperature gradients are fairly low (~20 to 25°C/km), and the tuffs within which the wells were drilled have low thermal conductivities (1 to 1.5 $Wm^{-1}K^{-1}$) resulting in anomalously low values of regional heat flow." Furthermore, more detailed maps (Sass et al., 1980, Figure 5; Sass et al., 1988, Figure 14) outline an area encompassing most of Pahute Mesa and Yucca Flat within which heat flow is less than 1.5 HFU, extending the Eureka Low southward. This is of interest principally because of the existence at Pahute Mesa of an exploratory hole, UE20f, that penetrates to a depth of more than 4 km and that displays an expressive thermal profile. Again quoting Sass and Lachenbruch (1982): "In the upper 1.5 km, the temperature gradient is 26°C/km and the calculated conductive heat flow is less than 40 mWm^{-2} [<1 HFU]. Below 1.5 km, there is a zone extending to nearly 3 km that is probably disturbed by a complex combination of lateral and vertical water flow. Below 3 km, the temperature profile is linear, and the gradient is 37°C/km. Thermal conductivities in this section are not well characterized, but reasonable values would result in heat-flow values between 80 and 100 mWm^{-2} [2 to 2.5 HFU] which is typical of the Basin and Range Province in general. The implication here is that water is carrying off much of the earth's heat in the upper 3 km and delivering it elsewhere." Sass et al. (1988) invoke similar arguments in explaining the deficiency (about 1 HFU less than the regional 2 HFU) and variability of surface heat flow in the vicinity of Yucca Mountain.

It is clear that Sass and his colleagues, in numerous reports of nearly two decades of research, have developed the following interpretation, which has evolved only slightly since their definition of the Eureka Low in 1971:

> The Eureka Low encompasses a broad area of southern Nevada beneath which the water table is generally deep, and which in broad aspects coincides with the recharge areas for large interbasin flow systems developed principally in carbonate aquifers, but also in volcanic aquifers.
>
> Heat is removed from the Eureka Low by lateral groundwater flow to areas beyond its boundaries.
>
> Surface heat flow is suppressed in much of the region by large thicknesses of unsaturated tuffs and alluvium, which have low thermal conductivities and in which the net groundwater flux is downward, thereby transporting conducted heat back down to zones of lateral flow beneath the water table. (Sass et al., (1988) also consider that vaporization and advective air flow may be an additional mechanism for the removal of heat from the unsaturated zone of Yucca Mountain, which is not clearly within the Eureka Low.)
>
> The lateral flow in the saturated zone is locally concentrated by hydrogeologic (including structural) features, resulting in significant perturbations of heat flow within and above the regional aquifer systems. Variability of surface heat flow on a smaller scale results from local deviations laterally and vertically, both upward and downward, as controlled by the interaction of local hydrogeology with the regional hydraulic-potential field.
>
> The small scale and common abruptness of the heat-flow variability within the depth of existing measurements (except below 3 km in UE20f) precludes an origin from deep-seated sources.
>
> Based on only sparse data, the heat flow beneath the regional aquifers is probably within the normal range (~2 HFU) for the Basin and Range Province and the southern Great Basin.

c. **Silica Geothermometer**

Swanberg and Morgan (1978) show the Battle Mountain high (>2.5 HFU) to be much larger than the area defined by Sass et al. (1971), based on an empirical relation between heat flow and silica concentrations in groundwater. Sass et al., (1980) included the Swanberg and Morgan (1978) 2.5 HFU contour on their heat-flow map of the western United States, remarking that the contrast between the interpretations was an unresolved paradox. The geochemically defined area extends southward from the Battle Mountain high, encompassing most of central Nevada, more than the western half of the Eureka Low, all of the Nevada Test Site and Yucca Mountain, and most of the Amargosa Desert.

The author indicates (Page 4-20) that, "a mystery posed by [these conflicting interpretations] can be readily resolved by recognizing that the deforming fractured medium is involved in the heat flow process ... [First, the] values of thermal conductivity as derived based on the laboratory measurements underestimate the actual in situ values, because they do not account for the dilated nature of the deforming fractured medium. Consequently, the intensities of heat flow are also underestimated... [Secondly] the deforming fractured medium, while it is being dilated, stores not only fluid but also the thermal energy. This causes the apparent decrease in the intensity of heat flowing through the deforming fractured medium."

The factors invoked by the author in explanation appear to conflict with each other and with other aspects of his conceptual model. For the upward transport of heat by conduction to be assisted by the fractured medium, thus correcting the "underestimates" of Sass, Lachenbruch, and their colleagues, requires upward flow of groundwater in the fractures. However, his model requires that, during dilation, the water table declines, presumably with downward flow to fill the enhanced storativity; this is required also for the introduction of cool water to store the thermal energy temporarily. Furthermore, his resolution of the apparent dilemma within the large area of the Eureka Low contrasts strongly with his contentions elsewhere in the manuscript that thermal and stress heterogeneities are responsible for variations of hydraulic potential on much smaller scales.

A more likely explanation was offered by several reviewers and by Sass et al. (1988). The heat-flow interpretations of Swanberg and Morgan (1978) for the silica geothermometer are of regional scale, presented on a map of the entire United States. Concentrations of silica in groundwater were averaged for 1° by 1° geographic areas (about 1/3 the size of the Eureka Low), and the empirical relation was established for data obtained nationwide, principally from carbonate aquifers. However, the southward extension of the Battle Mountain High encompasses groundwater systems flowing within or recharged through the extensive volcanic rocks of central and southern Nevada. As stated by Sass et al., (1988), "the abundance of highly soluble volcanic glass in the rhyolitic rocks of [central and] southern Nevada casts serious doubt on the validity of uncompensated silica geotemperatures in this area." Further evaluation of geochemical thermometry is planned during site characterization (DOE, (1988), Sections 8.3.1.2, 8.3.1.3, and 8.3.1.9).

The geothermal characteristics of the southern Great Basin, which provide the framework for understanding those of the Yucca Mountain area, seem not to be consistent with the author's conceptual model, in which thermal heterogeneities in the mantle -- both directly and through induced stress heterogeneity -- are necessary to explain the observed variations of hydraulic gradient in the region. Neither the sparse evidence nor published interpretations support the author's contention of heterogeneous heat flow, varying as much as 1.5 HFU, through the base of the flow system (Pages 3-22 and 4-19), despite the fact that the actual variation of surface heat flow varies by more than 2 HFU. The evidence that is currently available is not necessarily inconsistent with a variation in heat flux at the base of the hydrosphere of 1 or 2 HFUs, but the apparent hydrogeologic correlations with variations of surface heat flow, and the scales of those variations, are consistent with the regional redistribution of thermal energy by recharge-driven groundwater flow in the upper 1 km to 3 km of the crust.

3. TECTONIC PROCESSES AND CRUSTAL RESPONSE

a. The Dynamic Stress Field

A description of the Yucca Mountain region's "dynamic stress field" in Section 3.2.2 of the manuscript presents the Brady (1974, 1975, 1976) model of fault rupture. Although Brady's theory is not generally accepted as having practical value in earthquake prediction, because its postulated dilatant zone cannot be detected from the surface, this section introduces the idea that the "tectonic cycle" on a specific fault or in a strain domain is marked by the cyclic dilation and closure of microcracks that could provide a driving mechanism for episodic fluctuations in the water table. After examining this idea independently of the specifics of Brady's theory, the reviewers concluded that the discussion in this section was inadequate to support the conceptual model presented in the manuscript for the following reasons:

1. Effective stress changes are probably associated with earthquake nucleation and may have significant hydrologic effects that can be estimated from the volumetric strain estimates of Sibson et al.,(1975). Sibson et al. calculate that an M6 earthquake could expel on the order of $5x10^6$ cubic meters of fluid along a fault plane and its associated fractures from the collapse of a dilatant volume of 500 cubic kilometers. This is consistent with the surface expulsion of about 10^7 cubic meters in one year from the Matsushiro earthquake swarm (energetically equivalent to a single M6.3 event), as reported by Sibson et al., (1975) but originally reported by others. For comparison, if it is assumed that all of Skull Mountain is saturated with water from the elevation of Cane Spring (~4000 ft) down to the elevation of the water table in Frenchman Flat and Jackass Flats (~2400 ft) (Winograd and Thordarson, 1975), and that the change in water content from completely drained to completely saturated conditions is only one percent of bulk volume, then the amount of water contained in Skull Mountain would be on the order of $300x10^6$ cubic meters, or about 60 times the estimated outflow from an M6 earthquake. An earthquake of this magnitude is consistent with stress changes (10 to 100 bars) and volumetric strains (10^{-4} to 10^{-5}) considered typical of the southern Great Basin province. Hence, the growth and subsequent collapse of a dilatant zone, while offering a plausible mechanism for water to rise above the water table in a linear zone along a fault trace, does not seem likely to expel enough water to produce a groundwater mound with an areal extent on the order of 50 square kilometers and a height on the order of 600 m. Not only is the volume too large by almost two orders of magnitude, the height of the Skull Mountain "mound" (considered to be a perched water table by several reviewers) is much greater than the probable distance from the pre-event, humid-climate water table to the surface at Matsushiro. Finally, the time constant for the hydrologic effects at Matsushiro to grow and decay is on the order of a year, whereas the discharge from Cane Spring has been observed for decades.

2. Tectonic cycles in the vicinity of Yucca Mountain presumably have been relatively uniform for the past several million years, and the area has been subjected to a very large number of seismic events in response to ongoing regional deformation, resulting in pervasive fracturing and

faulting. These features, not the initiation of new ruptures in an intact rock mass, are expected to limit the magnitude of the stress change over the course of a seismic cycle to a small fraction of the failure stress of intact rock. Hence, the reviewers expect that failure theories developed to explain the rupture of intact rock to have little or no relevance to failure modes and associated hydrologic effects at Yucca Mountain.

b. **Tectonic Models**

The manuscript states (Page 3-6) that two tectonic models, detachment faults and right-lateral strike-slip faults associated with the Walker Lane, are being considered to account for the deformation observed at and near the Nevada Test Site. Actually, the Site Characterization Plan (DOE, 1988) mentions four models (i.e., planar rotational fault model, Walker Lane model, detachment model, and combined detachment and Walker Lane model). A rifting model and a leaky transform model have been mentioned elsewhere in connection with basaltic volcanism, and caldera models have been proposed to account for some of the faulting at Yucca Mountain. Other models may also be considered, as new information indicates the need.

The manuscript also states that it is not of great importance to know which tectonic model is applicable for the purposes of the hydrologic considerations being discussed. Alternative tectonic models are presented as equally supportive of the author's conceptual model. In the opinion of the reviewers, there are hydrologically important geometric and stress differences among various models. For example, the magnitude of the maximum horizontal stress in the upper crust is generally greater for the right-stepping strike-slip faulting model than for the detachment model. For right-stepping strike-slip faulting, interseismic strain build-up increases the magnitudes of the horizontal stresses, whereas for the detachment model it decreases them. Coseismic changes are also reversed. Although coupling effects may be expected in each tectonic model, initial and boundary conditions on stress, displacement, heat flow, and groundwater flow may differ significantly among alternative models.

D. CONCEPTUAL HYDROLOGIC MODEL

1. EQUATIONS OF POTENTIAL FLOW

In order to demonstrate a need for the introduction of coupled processes, the author discusses the simplifying assumptions that he believes represent the bases for the Project's current hydrologic modeling. The processes of concern to the author are thermomechanical coupling, which provides a driving mechanism, and hydromechanical coupling, which provides the effects.

There are two commingled issues in the manuscript: the technical content of the author's thesis and his view that the Project's efforts are technically inadequate. The paradigm that the author constructs to represent the level of complexity in hydrologic models and the degree of understanding of the Project's scientists does not portray the true position of the Project.

The standard saturated and unsaturated calculations to which the author refers are only initial steps to scope the modeling problem and to guide the field work. Such scoping models are part of the efforts to determine which coupled processes might be important and what geologic and hydrologic details are controls. Calculational models involving coupled processes have been and are being developed. The Project's approach is to use increasingly complex models as the data and field work demonstrate the need. The general feeling is that such models are of use if their complexity is demanded by the data, otherwise complexity may conceal phenomena of importance.

Current analyses by the Project address single-phase, steady-state, and transient flow in the saturated and in the unsaturated zones with spatially varying distribution of hydraulic properties (Waddell, 1982; Czarnecki and Waddell, 1984; Travis, 1984; Czarnecki, 1985; Barr and Miller, 1987; Dudley, et al, 1988). Variable initial conditions, transient boundary conditions, as well as transient changes in medium properties, are also considered (Birdsell and Travis, 1987). Current models are also able to handle long-term changes in recharge and discharge, in elevation of the water-table and in hydraulic properties such as storativity. Computer codes for treatment of two dimensional thermohydraulic flow in the saturated zone have been available for some time and are used to help elucidate geothermal systems. Extension of these codes to three dimensions is proceeding both within and outside the Project.

Further reply to the author's assertion of technical inadequacy occurs during the following discussion.

The manuscript presents the simplest forms of the Laplace and Poisson equations as the basis for the Project's hydrologic models. They are not incorrect, they merely describe flow in a uniform isotropic system, and do not represent the Yucca Mountain Project's current stage of development in hydrologic modeling. More general flow equations accommodate additional energy gradients as well as spatially variable hydraulic parameters and are routinely used to model confined and phreatic flow.

The report asserts on Page 5-1 that the prevailing conceptual model of the "flow system" at Yucca Mountain is "far too simple and much too far removed from reality." The approach used by the DOE to model groundwater movement in the saturated zone is characterized as single-phase, steady-state, and fully described by the Laplace equation. In fact, models for saturated zone circulation have been published that assume discharge and recharge, and have been used with non-steady boundary conditions to simulate increased recharge. Published models incorporate spatial variation of water content, spatially variable anisotropic conductivity, etc. (Travis, 1984). Variable initial conditions, transient boundary conditions, as well as transient changes in medium properties are also considered in current analyses (Birdsell and Travis, 1987). Long term changes in recharge and discharge, in elevation of the water table, and in quantities such as storativity and porosity (due to tectonic stress changes) can also be handled by current models. The Site Characterization Plan (DOE, 1988) contains general plans for investigating the possible effects of tectonism and igneous activity on the hydrologic system (Investigation 8.3.1.8.3).

The assertion that mathematical models of flow in the unsaturated zone at Yucca Mountain assume that "only downward flow is possible" is also incorrect. In fact, numerical studies are considering the possibility of lateral moisture flow in the unsaturated zone, and field studies will collect data for its evaluation. Results to date indicate that although lateral flow may be possible, it is not significant with respect to total flux, and especially not for radionuclide transport (Travis and Nuttal, 1987). Multi-phase flow, as well as both lateral movement of water and upward movement of water vapor (under both barometric and thermal impetus) are addressed in the current conceptual model of the unsaturated zone (Montazer and Wilson, 1984) and plans for further investigation are presented in the Site Characterization Plan (Investigation 8.3.1.2.2).

2. COUPLED TRANSPORT

Hydrologists have considered the state of in situ stress in analyzing aquifer responses (e.g., Witherspoon and Gale, 1977). In fact, much of what has been learned about this topic has come from studies associated with the geologic repository program (Tsang, 1987). It is true, however, that hydrologists usually do not address coupled thermal-mechanical-hydrologic processes in consideration of groundwater flow systems, but this is in part due to the fact that such coupling is needed only to discuss special circumstances (e.g., geothermal fields).

There is no question that the in situ stresses and the pore pressures in the saturated zone are coupled. This follows from the concept of effective stress introduced by Terzaghi (Terzaghi and Peck, 1948), and has become an important principle in soil and rock mechanics.

The hydraulic response of deformable fractures has been a research topic for some time among scientists supported by the DOE geologic repository program (Cook, 1987). Applications of the effective stress law to hydraulic transport properties of fractured rock have shown that the pore pressure contribution to conductivity changes is generally attenuated by some multiplier, which is reported by Walsh (1981) to be between 0.5 and 1.0. This effect is associated with channel flow and tends to reduce the efficiency of stress-hydrologic coupling.

As discussed below under the heading of constitutive relationships, there are multiple effects that tend to reduce the coupling efficiency. While the general relation presented by the manuscript for coupling between effective stress and rock-mass transport properties is adequate under gross simplifying assumptions, there are many specific effects that are not accounted for in the manuscript, such as: nonuniform aperture distribution (fracture geometry); pore pressure transients; fracture strength and rheology; and interlocking of fracture networks under applied shear. Reliable site specific information on these effects is scarce, so evaluation of the significance of in situ coupling must depend on estimates of the magnitude of the coupling functions, and on the extent to which test data are representative of in situ conditions. These concerns comprise some of the documented objectives for data collection, analysis, and modeling planned for site characterization.

The manuscript relies on hydromechanical coupling and thermomechanical coupling processes, and ignores other phenomena such as modification of the groundwater flow field due to chemical processes (de Marsily, 1986). This includes mineral dissolution and transport, cementation, gas drive, and the thermochemical effects on groundwater movement. These effects may be applicable to understanding the present characteristics of the groundwater system at Yucca Mountain, and could conceivably inhibit or facilitate radionuclide movement in the saturated zone depending on their interaction. Many of these possibilities will be addressed during site characterization, by data collection and/or modeling activities as described principally in Sections 8.3.1.2, 8.3.1.3, 8.3.1.8, and 8.3.1.17 of the Site Characterization Plan.

3. TECHNICAL ADEQUACY AND CONSISTENCY OF THE CONCEPTUAL PRESENTATION

The lengthy elementary introduction to the equations the author discusses should be eliminated. It would suffice to provide an introduction to hydrologic problems and a discussion of coupled processes by reference (i.e., de Marsily, 1986; Tsang, 1987). The reader would then have a better perspective on how the author's analysis fits into current science.

Coupling terms involving processes of specific interest to the author (thermomechanical and hydromechanical) are noticeably absent from the equations for flow (plates 2.2.1-4) and are introduced in an ad hoc fashion on Plate 3.4.4.1. The problem of the "critical surface" which the author specifies on the latter plate, appears to be a "moving boundary" problem. Careful definition and solution, numerically or analytically, of this Stefan problem would strengthen the author's arguments. It is reasonable for reviewers to ask to see the mathematical analysis on which so much of the argument hinges.

In the discussion of hydromechanical coupling the author introduces an extended form of Darcy's law for the flux. The ensuing commentary involves work of other authors and does not appear to be used in the text to support any arguments. If the analysis, including the proposed Galerkin formulation, were used in the ensuing discussion, then the document would benefit from a more detailed explanation of how and with what result. Otherwise, section 3.3.2 is an extended reference stating that others know how to do the problem, and should be replaced by a citation.

The author should be aware that his unconventional use or ambiguous definition of certain terms confounds the reader. Treatment of basic stress and strain concepts needs to be refined so that it agrees with conventional usage in mechanics. An important example of this need is shown by equating of "gradients of both the normal stress and the shear stress" to the condition of a "spatially heterogeneous strain energy field," (Page 4-24). Another example is the use of the terms "two phase flow" and "two phase flow field," which reviewers took to mean that the author considers water and heat to be phases in the same sense that liquid and vapor are. Also, the term "strain energy" is used to refer to elastic strain energy that is recoverable on unloading, but is also used in the manuscript for the energy expended during straining, which would include gravitational potential, heat, energy to create surface area, etc. Thus the total strain energy is said to be "substantially reduced" as a result of normal faulting (Page 3-3) and coseismic "removal" of strain energy is said to result in "...reduction in the magnitude of shear stresses along some fractures and/or in the increase in the magnitude of the effective normal stresses" (Page 4-28).

Another source of confusion is the association of the total strain energy magnitude with the magnitudes of particular components of the stress tensor, without fixing or otherwise controlling the other components (e.g., Pages 3-34 and 4-24). The relationship between stress, displacement, and strain energy in situ is probably much more complex than represented in the manuscript, which led reviewers to question the technical adequacy of the author's treatment of strain energy.

4. CONSTITUTIVE RELATIONSHIPS FOR STRESS-HYDROLOGIC COUPLING

The effects of effective stress on flow rate and fracture aperture have received extensive study, using, for example, horizontal saw-cut fractures (Gale, 1975) and in situ vertical fractures (Pratt et al., 1974). These studies indicate that fractures substantially close and hydraulic conductivity becomes relatively invariant with respect to stress changes, when the effective stress reaches approximately 5 MPa (for the relatively smooth saw-cuts) to 10 MPa (for natural fractures). These studies indicate that sensitivity of fracture hydraulic properties to changes in normal stress (perpendicular to fractures) is limited to depths shallower than about 1 km. However, shear dilation effects may operate below that depth, as discussed below.

Shear apparently is the principal source of fracture dilation at depths below 1 km. Fracture shear dilation has two aspects: elastic dilation at shear stress values significantly less than the peak shear strength, and inelastic shear dilation (associated with inelastic shear displacement) at stress values approaching the strength. From the published work of Barton et al. (1985), and others, there is evidence that the magnitude of inelastic dilation is significantly larger than the elastic component. The strength of a fracture is related to the effective normal stress, roughness, displacement history, and rock frictional properties. As pore pressure rises, the normal stress decreases and the strength diminishes, and the extent of inelastic shear dilation increases. This relationship is used in the manuscript as the conceptual basis for stress-hydrologic coupling.

The constitutive joint shear dilation relationship presented graphically in the manuscript (Plate 3.2.3-4) is based on bilinear behavior, with the onset of purely plastic displacement beginning at peak strength. Shear dilation is defined to increase linearly beginning before the onset of inelastic shear displacement, and increasing through the peak stress, up to a constant value corresponding to some finite shear displacement. Actual fracture samples tested in the laboratory exhibit asymptotic closure to some residual aperture but no well defined peak stress. Stiffness increases upon repeated loading and unloading, and stiff joints can be expected to exhibit smaller hydrologic changes in response to stress changes. Notwithstanding these departures, the bilinear relationship is a reasonable first approximation to actual fracture dilation response for discussion of the nature of stress-hydrologic coupling. However, the constitutive relationships used in the manuscript do not have numerical values on the axes.

The following paragraphs are extracted from the review comments, and describe various mechanisms that are related to the rock mass constitutive relationships. In principle these mechanisms reduce the importance of stress-hydrologic coupling, and according to the reviewers would be considered in a complete treatment of the subject, but were not considered in the manuscript.

1. Recognizing that fracture dilation is probably more important during post-peak deformation, existence of this phenomenon must mean that the geologic record contains evidence of slip in the form of ubiquitous displaced fractures and gouge. Alternatively, post-peak shear dilation is concentrated or does not occur. Evidence for ubiquitous inelastic shearing behavior is uncommon in rock masses, because shear displacement is inhibited by interlocking of blocks bounded by joints. Post-peak fracture deformation behavior is typically limited to major throughgoing discontinuities or fault zones, where significant shear displacement is commonly observed. The hydrologic significance of the shear dilation of a few features (in terms of the amount of fluid mobilized by stress changes) is quite different from dilation of ubiquitous joints.

2. The effects of inelastic shear deformation (displacement and dilation) would be expected to accumulate if such shear processes are associated with each seismic cycle. Generation of gouge and altered gouge products should eventually change the overall deformation response of the rock mass. Shear zones typically are much weaker than the unsheared rock mass, and are generally oriented ideally for responding to further seismic cycles, tending to limit the shear stress magnitude. Thus, even if ubiquitous, inelastic shear dilation occurred, progressive diminution of the dilation response would be expected with repeated stress cycles as major shear features developed. The cumulative number of seismic cycles is probably on the order of hundreds for major faults in the vicinity of Yucca Mountain, with tens of centimeters of displacement per event at recurrence intervals of tens of thousands of years (DOE, 1988).

3. The concept that small increases in pore pressure could initiate sliding along some fractures is consistent with the effective stress principle. Failure of certain rock slopes has been related to effective stress reduction due to groundwater, but in these cases the failed block was in some way bounded by a free surface. There is tremendous interlocking of fractures in a fractured rock mass; this is why many underground openings are as stable as they are. A principle of ground support design for fractured rock is that the rock mass around an opening can often support itself if small confinement (e.g. roof bolts) is provided at the wall of the opening. When rock mass failure occurs, shear zones and faults develop because major discontinuities, once they form, are much weaker than the interlocked rock mass. To the extent that significant shear dilation (and aquifer sensitivity to stress changes) is associated with post-peak, inelastic behavior of discontinuities, and that the ubiquitous fractures do not exhibit deformation over many tectonic cycles, then the sensitivity of bulk aquifer properties to stress changes is diminished by interlocking and the formation of faults and shear zones.

4. The introductory part of Chapter 4 of the manuscript (Page 4-2) states that the "majority of rocks comprising the water conducting medium can be represented as the Bingham substance or the B-K hybrid substance." This concept is unrelated to the conceptual model for groundwater movement in the report. Moreover, it is inconsistent with statements in Chapter 3 (Page 3-7), and it is irreconcilable with the idea of significant fracture flow. If fractures are to remain open and accessible for fluid transport through the seismic cycle, the material forming the fracture walls must remain effectively elastic.

5. STRESS AND STRAIN RELATIONSHIPS

Section 3 of the manuscript presents a hypothesis that spatial and temporal variations in stress and strain resulting from tectonic processes produce episodic changes in fracture aperture. In turn, these changes would produce significant areal and temporal variations in the elevation of the water table (Page 3-35).

The manuscript references the cumulative extension over the past 2 to 20 m.y. for the southern Great Basin estimated by Wernicke et al. (1982), and concludes that the resulting strain rate (10^{-15} to 10^{-14} s^{-1}) exceeds that which is possible from viscous flow (Page 3-7). There is abundant evidence that this range of strain rates is consistent with viscoelastic flow in much of the lower and middle crust (Walcott, 1970; Stocker and Ashby, 1973; Borns, 1987). Brittle deformation of the supra-crustal and upper crustal rocks in the Great Basin is a passive, second-order response to inelastic stretching and attenuation of the ductile lower crust. Regional tectonics are thus controlled and driven by viscous processes. This is true at all scales including the largest that could be considered relevant to the conceptual model of the groundwater system.

The manuscript states on Page 3-10 that "in the zone outside the displacement field, during the second phase of the tectonic cycle, deformation can be described by ... the Navier-Stokes equations of flow for a slow-moving, very viscous and slightly compressible fluid..." This appears to be inconsistent with the dismissal of viscous and viscoelastic phenomena in the upper crust, as discussed in the preceding paragraph. A similar inconsistency is present in the discussion of the Bingham and linear rheologic models on Page 4-2. The equivalent viscosity of supra-crustal and upper crustal materials at ambient conditions is too great for significant rheological flow at attainable stress levels. In addition, ductility is insignificant once strength is reduced by brittle failure, because flaws such as faults and shear zones tend to limit the maximum attainable shear stress. The author's discussion of inelastic rock mass behavior in the manuscript seems irrelevant.

6. **THERMAL COUPLING EFFECTS**

Several reviewers commented that thermally driven contributions may represent only a perturbation upon the overall groundwater flow system. If this were the case, then the mixed convection system would not be significantly different from a purely "forced" system driven by recharge, and possibly by coupling of aquifer characteristics to tectonic stress changes. The relative importance of buoyancy effects should be considered in a balanced treatment of hydro-thermo-mechanical coupling at Yucca Mountain, given the relatively weak nature of buoyancy forces compared to other hydraulic forces likely to be present. The possibility that heterogeneity in observed heat flow on the order of 1 HFU may be significant with respect to the groundwater flow regime will be investigated.

The manuscript states: "It can be shown that, at certain stress levels, the bulk thermal conductivity of a fractured rock medium is stress dependent..." The reviewers contend that this statement is insupportable for natural rock masses, either from theory or observation, if the meaning of "bulk thermal conductivity" is restricted to classical thermal conduction. In situ thermomechanical testing performed in Precambrian gneiss in Colorado (Hardin et al., 1981), and in welded tuff at G-tunnel (Zimmerman et al., 1986a; 1986b) produced no indications of significant coupling. During discussions with the author in the review process, he defined his use of the term "thermal conductivity" to include the capacity of an in situ rock mass to support all mechanisms of heat transfer.

Another concern of the reviewers was the notion in the manuscript (Page 3-3) that stress-induced changes in thermal conductivity could give rise to "a relatively rapid change in a local temperature field." The heat capacity of rock requires that small temperature changes be accompanied by heat transfer in amounts that are large compared to what can be accomplished by terrestrial heat flow in a time period corresponding to the seismic cycle. Simple calculations indicate that very long times are required to change in situ rock mass temperature, relative to seismic recurrence intervals.

Initially, heat transfer is limited to conduction. The author envisions that this results in the accumulation of heat in the subsurface rock mass, which is subsequently released by convective transport initiated by a dilatory tectonic event. Buoyancy forces that give rise to thermal convection are relatively weak, and thermally driven convection requires large temperature gradients to provide significant heat or fluid flow. The conditions that would be required for the thermal concept presented in Chapter 3 of the manuscript have not been identified at Yucca Mountain.

It seems likely that heterogeneities in observed temperature profiles reflect the effects of groundwater flow on heat transport rather than the converse. The usage of "thermally driven convection" in this review is an acknowledgment that another coupled effect is conceivable, whereby forced convection could be augmented as a transient effect when a tectonic event opens a conduit to deeper, hotter conditions. In concept, the flow that is "forced" through the new conduit is enhanced by buoyancy. To produce significant effects would seem to require particular conditions on the flow system, but this is one of the effects that will be investigated in the analysis activity that is documented in Section 8.3.1.8 of the Site Characterization Plan.

7. FLOW SYSTEM CONCEPTUALIZATION

The foregoing paragraphs have discussed coupled processes, and have indicated that the effects of such processes are at least plausible. Published work has been cited in addition to the subject manuscript in support of this discussion. However, the manuscript proceeds from this discussion to a conceptualization of hydrologic processes that was heavily criticized in review. The following is a critical discussion of several major issues raised in review of Chapter 3 of the manuscript.

The manuscript lists elements that would be included in a coupled model for Yucca Mountain. As stated by one of the reviewers: "it does not represent such a model for Yucca Mountain any more than listing the contaminant transport equations from a hydrology textbook constitutes a radionuclide transport model." In order to construct such a model one must not simply list the relevant equations and discuss possible constitutive relationships (as on Page 3-24 of the manuscript) but one must do sufficient work to select the most relevant forms of the equations and constitutive relationships, with all the attendant assumptions and conditions, and assemble them with enough rigor for evaluation.

The concept of a scalar field is used throughout the manuscript to refer to hydraulic potential, temperature, and elastic strain energy. The concept of a vector field is used for hydraulic flow velocity. The purpose for using such devices in this manuscript is not clear. The manuscript does not employ vector calculus (e.g., gradients of scalar fields) and does not otherwise relate the fields mathematically.

The response of the conceptual model to progressive extension in a normal faulting regime is presented in Plate 3.2.4-4 and on Page 3-15 of the manuscript. In the author's view, the water table is lowered because of increase in hydraulic storativity below the water table, brought about by extensional tectonic strain. As this occurs, the residual pore pressure below the descending water table is supposed to exceed hydrostatic conditions by a significant amount. This overpressure is postulated to explain the potentiometric observations from boreholes such as USW H-1 and UE25 p#1 at Yucca Mountain and possible additional overpressures at greater depth. However, the longevity of such transient overpressure is questionable because in situ hydraulic diffusivity is probably great enough for rapid dissipation of the energy stored in compression.

During questioning by the reviewers, the author maintained that the postulated lowering of the water table from tectonic causes would actually occur because of altered conductivity structure between recharge and discharge areas, instead of the one-dimensional storativity mechanism recounted above from Chapter 3 of the manuscript. This effect is potentially significant and will be examined during site characterization (see Site Characterization Plan Investigation 8.3.1.8.3). However, this modification does little to improve the plausibility of the mechanism, because the associated potentiometric transients would still be likely to dissipate rapidly, relative to interseismic time periods and to the postclosure time period for isolation. The postulated coseismic response of the water table is depicted in Plate 3.2.4-5 and accompanying discussion on Page 3-15 of the manuscript. Like the interseismic response, the magnitude of such a water table rise would be limited by the in situ hydraulic diffusivity.

In one reviewer's opinion, regional flow is dominated by a few zones of (relatively) very large permeability, such as intersecting systems of faults or zones of intense fracturing; these tend to be "durable" features over time periods important for waste isolation. The stress related effects would produce the greatest relative change in rocks with the lowest absolute permeabilities, and hence would be only local in scale. Without quantification, however, local could still be significant on the scale of Yucca Mountain.

The distributions of hydraulic potential with depth that are discussed in the manuscript and shown on the Plates, though idealized, can be identified with specific structural characteristics of a hydrologic system, as well as the mechanisms described by the author. For example, the potentiometric profile on Plate 3.2.4-4 (the dilatory response to tectonic extension), corresponds to that for upward flow in three situations: (1) from a confined aquifer through a leaky confining bed; (2) in response to a lateral decrease of permeability along deeper flow paths (e.g. more compressible rocks) causing flow to seek more permeable zones; or (3) resulting from a step-like gradient attendant to a change of rock type or a fault that retards flow, such as would occur on the downgradient side of a fault. The profile on Plate 3.2.4-5 (overpressure response to coseismic compression) occurs in areas of recharge to a permeable underdrain such as the lower carbonate aquifer beneath Yucca Flat and Frenchman Flat. The only feature that would differentiate between conditions that have already been identified in the Yucca Mountain region, and the concepts presented in the manuscript, is the progression of changes through the seismic cycle.

The discussion of rock mass response to a sudden pore pressure build-up (Page 3-36) contains a singular aspect. If increased pore pressure is restricted to an isolated volume as along a fault zone, the conduit will dilate causing compaction of the surrounding rock mass. However, it is not likely to dilate a fault by 3 m as suggested, because this would require a pressure greater than the effective normal stress on the fracture, and an extremely high fluid flow to the dilated fracture. Flow rate is restricted by rock mass conductivity, and for the case of fluid mobilized by large scale stress-induced reduction in formation storativity, the conductivity would also be reduced. Reviewers generally believed such large dilation of fault zones, by means of a mechanism similar to hydrofracture, to be implausible.

Moreover, rupture of a normal fault would increase the magnitude of the least principal stress, acting perpendicular to the fault plane (thus further resisting dilation).

The focus of discussion on Page 3-26 of the manuscript is the typical assumption of a lower "no flow" boundary in hydrologic models of the crust. The manuscript states that this assumption is appropriate for "forced" flow (driven by recharge), but not for "mixed" convection (also driven by thermal free convection). For "mixed" convection as presented in the manuscript, the upper part of the crust is identified as the region typically modeled, but which exchanges heat and fluid flux with the middle part. Thermally-driven convection takes place separately in the lower part, and in the middle and upper parts, in response to crustal heat generation and heat flow from the mantle. There is no appreciable difference between the upper and middle parts of this model in the manuscript. The model presented thus consists of: (1) a lower part in which heat is transferred by free convection of circulating fluids; (2) an impermeable barrier; and (3) an upper part in which fluids circulate by "mixed" convection.

A problem with this concept is the plausibility of thermally-driven convection in the middle and lower parts of the crust, where hydraulic conductivity is permanently reduced because of large in situ stress and geochemical fracture healing. A more reasonable model would be one in which the distribution of temperature and hydraulic potentials in the near surface flow system are controlled by: (1) regional hydrologic factors (including climatic variation and flow through lateral boundaries of the model); (2) distribution of hydraulic conductivity in the hydrosphere; (3) areal differences in temperature at the impermeable lower boundary of the near surface flow system; and (4) stress gradients.

In summary, the manuscript asserts that lateral differences of hydraulic potential at depth, on the order of tens of meters (corresponding to observations from the site), are expected from the characteristics of the proposed conceptual model. It does not mention that such differences are expected as a result of the geologic distribution of hydraulic properties within the flow system and that, as discussed in this review, there are good reasons to question the mechanisms proposed in the manuscript to account for these differences. However, it should be pointed out that the characterization of the major features of the durable flow system at Yucca Mountain is important unfinished business.

The manuscript explains piezometric observations from Yucca Mountain, including the flat water table and the steep water table in bounding regions west and north of Yucca Mountain, in terms of in situ stress heterogeneity. Although this is possible, observations of the water table are not sufficient to validate the mechanisms proposed. One reviewer compared Yucca Mountain to the Precambrian of the Front Range, Colorado, where the water table closely follows topography, because the decrease of conductivity with depth controls the transmissivity.

The theoretical problems identified do not invalidate the idea that coupling between groundwater flow and tectonic deformation could be important. Most reviewers readily agree that the topic deserves further investigation. However, the problems illustrate that: (1) much of the complexity and formalism could be eliminated from the manuscript without materially affecting its impact, and (2) the author fails to develop a quantitative model using the information and concepts he presents.

8. EFFECTS OF TECTONIC COUPLING ON THE VADOSE ZONE

a. Fracture Flow in the Vadose Zone

In the development of the conceptual model, the manuscript states on pages 3-15, 3-17, and 3-18 that increased fracture apertures, attending stress relaxation, increases hydraulic conductivity and thus the tendency for vadose water to flow in fractures. The same assertion appears in the manuscript conclusions in Pages 5-2 through 5-5. (On Pages 5-4 and 5-5, however, the "relaxed" state is associated with interstitial flow.) The claimed relationship was considered by the reviewers to be erroneous with reference to Montazer and Wilson (1984), Ross (1984), Wang and Narasimhan (1985), and Klavetter and Peters (1985).

At less than complete saturation, the rock matrix contains water with pressure less than that of the air and vapor in the fractures and matrix interstices; the water is under capillary tension or suction. Consequently, there is a persistent tendency for water, if present on the fracture walls, to be imbibed into the matrix at rates that are independent of fracture aperture. Fractures constitute capillary barriers to the movement of water in the vadose zone. Increased rates of percolation (flux) could indeed increase matrix saturation and decrease the rate of imbibition from fractures into the matrix. This would result in an increased tendency for fracture flow that could be realized locally where flow is concentrated by lithologic and structural features. Such spatially concentrated flow would tend to be dispersed again where fracture pathways end, such as downward from well fractured welded tuffs into less fractured nonwelded and bedded tuffs. Similarly, dispersion of flow in pervasively fractured rocks would increase the surface area available to the imbibition process. There is currently uncertainty, however, as to the possible importance of alteration minerals on fracture surfaces. The possibility that they may impede the imbibition process requires study during site characterization.

Current evidence indicates that existing fracture apertures do not limit flux into the vadose zone. By increasing ventilation of the fracture system, stress relaxation might, in fact, enhance drying of fracture walls, removing matrix flux from the rock mass and increasing the tendency for imbibition. The assertions in the manuscript are not supported by theory, by experimental results, or by observations.

b. Forced Gas Movement

It is proposed in the manuscript (Pages 5-4 and 3-17) that gases in the vadose zone will move in response to the "pumping" action caused by excursions of the water-table altitude. Reduction of the volume available to gases and vapor requires an equal reduction of water storativity volume beneath the perturbed water table. Therefore, only spatially extensive closure of fractures could raise the water table enough to produce significant reduction of vadose-zone storativity. Such changes, if credible at all, could occur only at geologic rates, over thousands of years or more. Even at incredibly fast rates, such as meters of water-table change per year, the proposed mechanism would be vanishingly small compared to daily thermal and seasonal barometric ventilation of the rock mass.

E. GROUNDWATER MOUNDS

The manuscript proposes three effects of tectonism that bear significantly on the effectiveness of the vadose (unsaturated) zone at Yucca Mountain as a primary barrier to the loss of containment by waste packages and to the isolation of radionuclides at the site when containment has been breached. Two of these proposed effects (an increased tendency for flow in the vadose zone to occur in fractures rather than in the rock matrix when fracture apertures increase, and forced flow of gases in the vadose zone by rises of the water table) were discussed previously in section II.D of the review report. The third, and potentially the most serious of the proposed effects, is the postulated mounding of the water table by upward injection of groundwater due to stress-induced reduction of fracture apertures at depth, or due to hydrothermal convection in a deep, open fault zone.

A water-table rise would be attended by three stages of increasingly serious consequences:

1. Foreshortening of the vadose-zone barrier beneath the repository.

2. Submergence of the repository by waters that, presumably, would be more corrosive.

3. Intersection of the elevated water table with the land surface, drastically shortening flow paths and travel times to the biosphere.

1. CONCEPT AND RECOGNITION CRITERIA

Both the proposed mechanisms and interpretation of field evidence for thermal- and stress-driven excursions of the water table are fundamental to the thesis of the manuscript. The conceptual basis is developed in Section 3 of the manuscript within the context of crustal-scale geothermal and stress fields and their proposed effects on the total hydrologic system. The subsections that are most directly applicable to the hypothesis of tectonic mounding are found in Pages 3-13 through 3-19, 3-24 through 3-27, and 3-32 through 3-37.

Briefly, the concept is that water-table mounds form over areas of anomalously high heat flow, over stress heterogeneities that close fracture apertures at depth, or in areas where both processes are occurring, whether or not they are linked. The resulting large hydraulic potentials at depth are proposed to force deep groundwater upward into the previous vadose zone. (An alternative proposed mechanism not in the manuscript, but explained by the author in comment-resolution meetings, is lateral invasion of the vadose zone by water rising hydrothermally along preferentially open fault or fracture zones that are continuous from great depths.) Mounds may either be active, responding to currently existing thermal or stress conditions, or be undrained relicts from past thermal or stress conditions.

It is proposed on Pages 4-4 and 4-5 that "perched waters represent[ing] meteoric waters caught during their downward passage through the vadose zone ...should not exhibit hydraulic, thermal and chemical affiliation with waters occurring below the water table." In contrast, tectonically formed mounds "would occur in areas where the in situ stress conditions are such that a true value of hydraulic potentials can display itself in the near ground surface conditions" and "...the [tectonically] perched waters, although diluted by fresh infiltrating water, should exhibit either hydraulic or thermal and chemical affiliation with waters occurring below the water table." These statements are unclear; however, taken in the context of the entire manuscript, they seem to imply the following:

(1) A continuum of saturation and of hydraulic potential, in terms of progressively increasing potentials with depth, should occur through and beneath active tectonic mounds (or toward the source in the case of laterally spreading hydrothermal water from a fault zone), but there should not be a continuum of either saturation or potential between perched meteoric waters and the saturated zone beneath. It is also inherent in the term "mound" that the areal potentiometric configuration is such that potential is higher in the mound than it is on the surrounding unperturbed water table, or is at least positive relative to a projected regional potentiometric gradient. An alternative non-tectonic case, not considered explicitly in the manuscript, is that in which there is a continuum of saturation and potential through an elevated body of rock to an aquifer below that has a lower hydraulic potential. The gradient in this case is downward rather than upward, and the contrast of permeability is so great that hydraulic isolation is closely approached. Winograd and Thordarson (1975) apply the term "semi-perched" to such water in the elevated rock mass. Presumably, relict hydraulic mounds could mimic either perched or semi-perched meteoric waters in terms of hydraulic "affiliation." It is also conceivable that, in advanced stages of drainage, relict mounds could become unsaturated.

(2) Water in an active tectonic mound should be of higher temperature than that which is characteristic of the surrounding region at similar depths. In the pressure-driven mound there should be an upward thermal gradient; i.e., the temperature should increase with depth. Presumably, there should not be a strong inflection of the gradient at the depth of the surrounding water table. Temperature should increase toward the source fault in the case of a hydrothermal convective mound. Penetration of an active hydrothermal mound should reveal higher temperatures in the laterally spreading mound than in the uninvaded rocks above and below. Perched or semi-perched meteoric water should be cooler than or equilibrated with the characteristic temperature at its depth. A strong inflection of the temperature profile at the water table would be a revealing though not a necessary characteristic of the perched case. A relict mound would tend to equilibrate thermally with its host rock. It would evolve from warmer than to about the same as the characteristic temperature and, if mixed with downward-percolating meteoric waters, could be cooler. Consequently, relict mounds could mimic perched or semi-perched meteoric waters also in terms of thermal "affiliation."

(3) The chemical composition of water in an active or a recently relict mound should be quite similar to that of water from its source within the surrounding saturated zone, but meteoric water that is perched in (or in transit through) the vadose zone should not, according to the general criteria expressed in the manuscript on Pages 4-4 and 4-5. Elsewhere in the manuscript, different and more specific chemical criteria are proposed; these are discussed below.

a. <u>Discussion of Basic Criteria</u>

The criteria relative to hydraulic and thermal relationships appear to be correct for recognition of locally rising flowpaths. The difference between the views expressed in the manuscript and those of the reviewers relate to the cause of upward flow rather than its occurrence. In the opinions of the reviewers, local upward gradients are an expected feature of recharge-driven flow ("forced" flow in the manuscript) in a topographically and hydrogeologically complex terrane. Such gradients also are a fundamental hydraulic requirement at and near discharge areas in a simple homogeneous, isotropic hydrogeologic model. In the case of discharge areas, upward flow and consequent higher temperatures occur in hydraulic sinks (with respect to groundwater potential) rather than mounds. At intermediate positions in a groundwater basin, both downward and upward flow directions are a consequence of the spatial distribution of permeability, resulting in irregularities in both the vertical and areal distributions of hydraulic potential and temperature. Normally, these irregularities result only in linear zones of steep gradients ("steps") as depicted on maps.

The chemical criterion, based on the vague term "affiliation," was considered by reviewers to offer no testable hypothesis and to be fundamentally ambiguous. There certainly should be "chemical affiliation" between water in the zone of saturation and that in vadose zones of principal recharge areas, though the water will mature chemically along flowpaths, both vadose and saturated. Rock-water interactions will progress at rates governed by the surface area of the reactive minerals and glasses, the previous reactive history of the rocks, the degree of equilibrium between the water and the various hosts through which it passes, and various physiochemical factors such as temperature, pH, oxidation potential, and partial pressure of carbon dioxide. Residence times will vary among individual flowpaths and, along these, in rocks of differing hydraulic properties. The resulting chemical relationships within the vadose zone, within the saturated zone, and between the two are expected to be quite complex in terms of concentrations of dissolved constituents and their relative concentrations. They may be interpretable only on a specific, case-by-case basis or in terms of broad regional relationships in which local variations become homogenized.

The implication that downward-percolating or perched meteoric waters should have at least somewhat lower concentrations of dissolved solids than those beneath the water table is true only on a regionally homogenized, flux-weighted average. In reality, one would expect a distribution of vadose-zone water salinity as compared with the proportion of recharge contributed to the saturated zone. Vadose water in areas that contribute a relatively large share of the recharge flux should indeed have somewhat lower salinity than the more mature water of the saturated zone. However, in areas of relatively low vertical permeability, vadose water is subject to chemical reaction for longer residence times and may have salinities that substantially exceed that of the average recharge flux. The distinction between "active" and "inactive" waters is commonly understood by hydrologists to apply also at a much smaller areal scale, specifically to distinguish between water moving slowly through rock interstices and that moving more rapidly through fractures and fault zones within the same rock mass.

b. Specific Chemical Criteria

The manuscript mentions in various contexts chemical factors that are proposed to differentiate between meteoric water and tectonically mounded water in the vadose zone. These factors include the following:

(1) "Perched water and[/or] interstitial pore water [that] are chemically different from the fracture water." (Pages 4-7, 4-30, 5-4, 5-6, 5-7, and 5-8.) The proposed conceptual model **requires** [emphasis added] the chemistry of interstitial pore water in the vadose zone to be different from the chemistry of water currently residing in fractures." (Pages 5-7)

(2) "High total dissolved solids..." with specific mention in various places of sodium, bicarbonate, sulfate, chloride, and silica (Pages 4-6, 4-7, and 4-29).

(3) "High content of ... sulfate...," in places qualified as "relatively high" (Pages 4-7 and 4-29).

These criteria are introduced in the manuscript in association with proposed mounds near Skull Mountain and at Rainier Mesa. They are discussed in the corresponding sections below.

c. Test of Criteria Against an Active, Nontectonic Mound

A currently active mound of the water table, recharge driven rather than tectonically driven, was hypothesized by Dudley and Larson (1976) to occur in the vicinity of Devils Hole on the east side of Ash Meadows. Regional flow approaches the Ash Meadows discharge area from the northeast in relatively deep confined zones in the lower carbonate aquifer, as evidenced by a water temperature of 34°C. On the east side of Ash Meadows, the transmissive zones in the regional aquifer are apparently truncated by one or more NNE-trending faults, and water rises through a complex pattern of faults that segment the hills, as interpreted by Winograd and Thordarson (1975) and by Dudley and Larson (1976). The high potential in the resulting mound is relieved partly by discharge directly from the carbonate rocks at the Five Springs area (34.5°C) and at Point of Rocks (34°C). However, most of the current discharge is eastward into local travertine and lacustrine limestone aquifers, supplying high rates of warm (28 to 33°C) discharge to several springs in central and southeastern Ash Meadows. A shallower transmissive zone of the lower carbonate aquifer (about 29°C) supplies Longstreet Spring (28°C), Rogers Spring (29°C), and Fairbanks Spring (28°C) in northern Ash Meadows. The chemistry of waters from the major sources of discharge of both temperature categories are essentially identical to ("affiliated with") that in the source aquifer; however, waters that spend relatively longer times in residence in the alluvial aquifer, discharging at smaller and lower-temperature springs, evolve to different and variable compositions.

The Devil's Hole mound clearly meets the claimed criteria for a mound formed by active tectonism. In this case, however, the source is a thoroughly studied and characterized regional aquifer, one in which the transmissive zones are irregularly solution-enlarged, essentially undeformable pathways. Meeting of both vertical and areal criteria for hydraulic potential, temperature, and hydrochemistry still fails to demonstrate hydrotectonic mounding. It is apparent that no simple, unambiguous set of criteria has been identified in the manuscript to test the case of proposed active mounding.

2. EVALUATION OF PROPOSED MOUNDS

a. Beatty Area

On Page 4-5 of the manuscript, with reference to Plate 4.2-1, it is stated: "Approximately 5 miles and 10 miles north from Beatty, (up the regional gradient), the water table is situated at altitudes 3,800 feet and 4,000 feet..., respectively. Around the town of Beatty there is a cluster of springs [actually, the sites circled on the plate include No. 25, a spring, and Nos. 26 and 27, both wells] whose orifices are situated at altitudes 4,000 feet and higher. The results of chemical analyses and of temperature measurements performed on waters discharging from these springs are presented on Plate 4.2-2. Clearly, a deep rooted hydraulic mound, some 200 or 300 feet high, is present...[this indicates], in no uncertain terms, that more than just a simple 'forced' convection flow process is involved." Several reviewers provided comments that address these claims.

Beatty itself is at an altitude of about 3,300 ft,and the numbered sites are at the following approximate altitudes as determined from the USGS topographic maps of the 15-minute Bare Mountain and Bullfrog quadrangles: spring, site 25--3,370 ft; well, site 26--3,380 ft; well, site 27--3,295 ft. Along the Amargosa River through Oasis Valley, the water table closely approximates the land surface, with springs discharging on the valley floor and from the lower parts of the adjacent slopes. As described by Malmberg and Eakin (1962), Blankennagel and Weir (1973), Winograd and Thordarson (1975), and White (1979), Oasis Valley is the principal discharge area for regional flow from part of Pahute Mesa and for lesser, locally derived flow from the Bullfrog Hills and the Springdale area. Potentiometric levels of discharges in and near the valley floor, including the correct altitudes for sites 25, 26, and 27, are lower than those to the east, north, and west, although they are not lower than those to the south, where the thin alluvium of Oasis Valley discharges into the transmissive sediments of the Amargosa Desert. In the sense of groundwater hydraulics, the area would be described more appropriately as an incompletely closed sink rather than as a mound, and the correct altitudes for the springs and wells cited by the author shows the Beatty area to be within this sink.

Subsurface temperature profiles are not available, but examination of Plate 4.2-2 reveals nothing remarkable regarding the temperatures at sites 25 (24°C), 26 (21.5°C), and 27 (20°C) relative to the sample set as a whole. Some are cooler and many are warmer; the range is from 18°C to 41°C. The warmest subset comprises springs that discharge directly from the tuffs, indicating that flow paths from the recharge areas to Oasis Valley reach depths of a kilometer or more, judging from the many temperature logs in the region as reported by Sass and Lachenbruch (1982).

Plate 4.2-2 reveals nothing that is anomalous in the chemistry of these sources within the context of the entire suite of samples. Several figures in White (1979) show the following with respect to total dissolved solids (TDS):

(a) Discharge from the tuffaceous aquifers ranges in TDS from about 350 to almost 600 mg/L; sample 25, at 384 mg/L, is well within but at the low end of this range.

(b) Water from site 27, at 814 mg/L, is consistent with the trend for the Thirsty Canyon - Oasis Valley alluvial-aquifer flowpath; White (1979) attributes the down-gradient increase of TDS to concentration by evapotranspiration from the shallow saturated zone.

(c) Water from the alluvium in the Indian Springs flowpath (sample 26) is higher in TDS than that upgradient on the flowpath (samples 7 and 8) but much lower than that in the Oasis Valley alluvial aquifer, to which it is tributary.

White's (1979) analyses of chemical relationships of water in Oasis Valley are very thorough and consistent both internally and with other regional data. The samples in question were not exceptions. White (1979) does state that sulfate concentrations are high in comparison with those of Pahute Mesa water, suggesting a possible hydrothermal source. Note, however, that the availability of sulfur in volcanic glasses was recognized in the mid-1980s; (e.g., Devine et al., 1984).

One reviewer pointed out that west of Beatty, in the Bullfrog Hills (an area a few kilometers distant from the author's Beatty mound), several springs and wells do occur at altitudes of 4000 feet and higher (Waddell et al., 1984). There are few data pertaining to these occurrences. White (1979) does give temperatures and chemical data for three (sampling sites 7, 8, and 15), but corresponding data for the others are not known to exist; also, there are no known continuous or periodic discharge data and no subsurface data. The conventional hydrogeologic interpretation is that these occurrences represent perched water, but it is more conservative to regard them as presently unresolved. However, they are not germane to the specific cases of groundwater mounds cited by the author. If, during site characterization, other data support critical parts of the author's hypotheses, then the review committee would favor further investigation of the Bullfrog Hills area.

To summarize the evidence relating to the proposed Beatty mound, the vertical aspect of the first criterion would probably be met if data were available, i.e., saturation is continuous and hydraulic potentials probably increase with depth in the area encircled on Plate 4.2-1. The fundamental requirement that the mound be potentiometrically higher than the projected trend of the surrounding water table is not met, when only data cited by the author are considered. However, it may be met if springs to the west in the Bullfrog Hills are not fed by perched aquifers, as assumed by Waddell et al. (1984). The second criterion also cannot be tested in terms of depth characteristics, but we would concede that the temperature probably increases with depth; i.e., it decreases from deep, warm parts of the flowpath toward the surface. However, the requirement for active tectonic mounding that temperatures exceed, or at least equal, those in neighboring areas at similar depths cannot be tested with the data available. The chemical criterion is met in terms of "affiliation" with the saturated zone, but simply because the samples are from the saturated zone. On the basis of available data and the considerations above, the presence of a groundwater mound in the Bullfrog Hills cannot be ruled out. A majority of the review believe that a non-tectonic origin is more likely than a tectonic origin, but this question remains indeterminate. The data specifically cited by the author completely fail to support the "Beatty mound" as proposed, despite his use of such superlatives as "clearly" and "in no uncertain terms."

b. **Skull Mountain Area**

The second area proposed in the manuscript as a possible mound is along the divide between Frenchman Flat and Jackass Flats, including the Cane Spring area and Skull Mountain to the southwest. In the discussion on Pages 4-5 and 4-6, the area is apparently interpreted to be an active mound rather than a relict one. The authors whose data are cited (Winograd and Thordarson, 1975) also describe this as an area of mounding but in the sense of hydrogeologic rather than hydrotectonic origin. As shown on Plate 4.2-3, which is reproduced from Figure 31 of Winograd and Thordarson (1975), several test holes and water wells show the water table beneath central and eastern Frenchman Flat to be at an altitude of about 2,400 ft. According to Winograd and Thordarson (1975), the top of the lower carbonate aquifer is 1,000 ft or more (as much as 3,500 ft) beneath the water table; the potentiometric level is about 2,380 ft, or 10 to 30 ft less than that represented by the water table. To the west of the Skull Mountain area, in Jackass Flats, the water table is also at approximately 2,400 ft.

As stated in the manuscript and shown on Plate 4.2-3, water levels in two wells on the western edge of Frenchman Flat are at altitudes of approximately 3,000 ft. The structurally elevated rocks of the divide area are saturated at altitudes of about 4,000 ft, as evidenced by well data and springs. Consequently, the areal hydraulic relationships meet the criteria for active or relict hydrotectonic mounding, as well as those for hydrogeologic perching of downward percolation as interpreted by Winograd and Thordarson (1975).

The manuscript (Page 4-6) closely paraphrases, though without citation, Winograd and Thordarson (1975, PageC-58) in describing the occurrence of water in test well 73-68. Based on the drillers' first reporting of water when drilling at a depth of 660 ft, as compared with a depth to water of 518 ft after the completion of drilling, the manuscript states that this indicates an increase of hydraulic potential with depth. However, drillers commonly "report water" upon detecting dilution of drilling fluids. In the tuff aquitard of the Skull Mountain area, drilling could have proceeded through saturated rock for a considerable depth before penetration of a sufficiently permeable zone to cause noticeable dilution. Hence, the only measured level in this hole was at 518 feet, as described by Winograd and Thordarson (1975).

Test well 73-66, commonly known as Test Well F, provides potentiometric data that preclude upward flow to sustain active mounding. As shown on Plate 4.2-3, two measurements were obtained in the Tertiary section with the deeper interval (rocks of Pavits Spring and Tuff of Crater Flat, Plate 4.2-3a) having a potentiometric level that is 454 ft lower than that in the higher Wahmonie Formation. The chemical data from these intervals are selected for inclusion in the manuscript to support the mounding hypothesis, but the conflicting potentiometric data are ignored. The latter are consistent with the criteria for relict mounding but are equally consistent with those for perching or semi-perching of downward percolating meteoric water.

As thermal support of the mounding hypothesis, the manuscript refers only to the relatively high temperature (64.5°C) of the water sample obtained from the lower carbonate aquifer in the depth interval 3,140 to 3,400 ft. The flow path leading to the point of sampling is unknown but is apparently quite deep. The temperatures and vertical gradient defined by the upper two sampling zones (22°C at 77 to 693 ft; 33.5°C at 1,565 to 1,695 ft) are within the normal range at comparable depths for boreholes within a 15-mile radius (Plates 4.6.2-1 and 4.6.2-6). The temperature at the static water level, a depth of about 1,800 ft, is 49°C (Sass and Lachenbruch, 1982; manuscript Plate 4.6.2-6). However, projection of the thermal gradient downward from the sampled zones in the Tertiary rocks intersects the 1,800 ft depth at a temperature in the range of 34 to 35°C, requiring a very strong (14 to 15°C) inflection of the gradient in the vicinity of the water table; this assumes, of course, that the temperatures of the water samples are representative of those in the upper two zones. The temperatures are not consistent with the thermal criteria for active mounding, but they are consistent with those for perched infiltrating water or for a relict mound that has equilibrated thermally with its host rock.

As compared with regional averages for water in the lower carbonate aquifer, water from the lowermost zone in Test Well F is about 25 percent higher in total dissolved solids and more than 200 percent higher in sulfate. Together with the high temperature, this suggests that the flow path that was sampled is not a principal pathway in the aquifer. The somewhat anomalous water is not known to be inconsistent with origin from a deeper, unknown source. Even allowing for chemical interactions, however, it is difficult to consider this water as the source for that perched in the Tertiary rocks or to be derived from the same source, as noted by a reviewer. In the upper zone, for example, the combination of reactions and dilution would have to accomplish more than a five-fold reduction of sulfate with a three-fold increase of chloride and with a nearly complete loss of calcium and magnesium and a 50 percent reduction of potassium, all with about a 40 percent reduction of dissolved-solids concentrations.

The deeper Tertiary zone (1,565 to 1,695 ft) presents somewhat of an enigma. unlike the upper zone, its water is not typical of that in the tuff aquitard, being strongly enriched in sodium, carbonate plus bicarbonate, and sulfate. the chemistry supports neither a source from the lower zone nor the common chemical evolution of water in the tuff aquitard. Among the possible explanations are:

(a) the chemistry has resulted from reaction with the evaporate-rich rocks of Pavits Spring, as suggested by Winograd and Thordarson (1975); or,

(b) the chemistry was influenced by the invasion of drilling fluids, possibly supported by the high pH (8.8).

On Page 4-6, the manuscript implies that the proposed mound is located over a negative anomaly of seismic P-wave velocity and states that this "...suggests that the involvement of tectonic factors ... should be seriously considered." As discussed previously in this review (Section II.C), Test Well F and the area of proposed mounding lie to the east of the anomaly.

In summary, the proposed Skull Mountain hydrotectonic mound does not meet the criteria for an active mound, and it meets those for a relict mound only hydraulically and thermally; i.e., only in those aspects that mimic the criteria for perched or semi-perched infiltrating water. Chemical incompatibility of the water in the tuffs with that in the underlying aquifer seems to preclude identification of even a relict mound.

c. **Rainier Mesa**

Rainier Mesa, in north-central Nevada Test Site, is on the southeastern periphery of the extensive volcanic upland of the Belted Range, Pahute Mesa, and Timber Mountain. To the southeast, in Yucca Flat, equivalent and associated volcanic rocks are down-faulted thousands of feet and occur beneath the regional water table. Beneath Rainier Mesa, however, the regional water table is in Paleozoic dolomites (lower carbonate aquifer) that underlie the tuff sequence. Approximately the lower half (about 1,000 ft) of the volcanic section is composed of zeolitized tuffs having low interstitial permeability but high porosity. Tunnels driven into these tuffs for nuclear weapons tests have encountered discharge of water from fractures and faults. Discharge from the fractures has been short-lived, but that from faults has been quite persistent. The manuscript, citing the studies of Winograd and Thordarson (1975) and Russell (1987), describes the general setting, including water chemistry, on Pages 4-6 and 4-7 and the effects of nuclear explosions on water discharge and chemistry on Pages 4-29 and 4-30.

A conclusion that is not in dispute is that water that is higher in dissolved solids and concentrations of most constituents is squeezed, by the compaction attending nuclear explosions, from the interstices of the zeolitized tuffs into the fractures and faults. This results in temporarily increased discharges of water in which most dissolved constituents are present in higher concentrations. Two alternatives for the source of sulfate, drilling activities and relict (synvolcanic) waters, are offered in the manuscript before the third and preferred possibility of relict mounding is presented.

According to the manuscript on Page 4-7, "The formation of this mound would have to be related to a tectonic event which would involve local alteration of the in situ stress field allowing for the full display of hydraulic potentials in the 'mixed' convection flow field. This mound would be similar, but older, to the mound present [sic] in Beatty and one inferred to be present at Skull Mountain."

The concentrations of sulfate in the perched water of Rainier Mesa are described as "relatively high" with reference to Plate 4.2-7 and to exhibit "large increases" after nuclear weapons detonations. Plate 4.2-7, is highly misleading because it reproduces selectively only one of 17 sets of data presented in its cited source (Winograd and Thordarson, 1975, Table 8). The source table, reproduced here as Table II.E-1, shows that only one data set,

Table II.E-1. Chemical constituents of ground water in the Nevada Test Site and vicinity. All constituents reported in milliequivalents per liter, except as indicated. Reproduced from Winograd and Thordarson, 1975.

Map number and area (pl. 3)		Hydrogeologic setting	Number of samples[1]	Ca+Mg			Na+K			HCO_3+CO_3			SO_4+Cl			$\frac{Ca+Mg}{Ca+Mg+Na+K} \times 100$ (percent)	$\frac{HCO_3+CO_3}{HCO_3+CO_3+SO_4+Cl} \times 100$ (percent)	SiO_2 (mg/l)			Dissolved solids (mg/l) (Residue on evaporation at 180°C)			Data sources
				Range	Median	Mean	Range	Median	Mean	Range	Median	Mean	Range	Median	Mean			Range	Median	Mean	Range	Median	Mean	
Calcium magnesium bicarbonate facies																	**Calcium magnesium bicarbonate facies — Continued**							
IA	Spring Mountains[2]	Major recharge area; highest parts underlain principally by Paleozoic carbonate rocks. Water sampled from perched springs.	4	4.6–5.5	4.9	5.0	0.05–0.7	0.10	0.3	4.4–5.5	4.7	4.8	0.15–0.60	0.38	0.38	98	92	6.5–33	8.4	14	232–351	248	270	Maxey and Jameson (1948); U.S. Geol. Survey files, Denver, Colo.
IB	Northwest Las Vegas Valley; southern Three Lakes Valley; southern Indian Springs Valley.	Piedmont alluvial plain bordering Spring Mountains on the northeast. Water sampled from both valley-fill and lower carbonate aquifers.	10	3.1–6.3	4.0	4.2	.08–.71	.30	.34	3.0–4.7	3.7	3.7	40–2.7	48	.77	93	88	6.6–25	15(9)	15	200–340	216	235	Do.
IC	Pahrump Valley[3]	Piedmont alluvial plain bordering Spring Mountains on the southwest. Water sampled from valley-fill aquifer only.	26	3.2–12	4.5	5.2	.22–2.0	.57(25)	.86	3.3–8.5	3.9	4.2		1.1	1.8	89	80	8–38	20(21)	20	208–822	290(25)	354	Maxey and Jameson (1948); U.S. Geol. Survey files, Carson City, Nev.
ID	Pahranagat Valley	Major discharge area for lower carbonate aquifer; high-yield springs sampled.	3	3.4–4.2	4.1	3.9	1.1–1.6	1.4	1.4	3.8–4.5	4.3	4.2	.79–1.1	1.0	1.0	75	81	31–33	31	32	---	277 (1)	---	Eakin (1963)
Sodium potassium bicarbonate facies																	**Sodium potassium bicarbonate facies — Continued**							
IIA-1	Rainier Mesa	Minor recharge area; ground water perched in tuff aquitard sampled.	24	0.01–1	.1	.3	0.72–4.3	1.4	1.7	0.79–2.3	1.2(23)	1.3	0.23–1.1	0.48 (23)	0.50	7	71	34–126	52	54	91–424	192	220	Clebsch and Barker (1960).
IIA-2	Hills west of Yucca and Frenchman Flats.	Minor recharge area; ground water perched in tuff and lava-flow aquitards sampled.	9	.16–2.4	.87	.93	1.0–4.5	1.7	1.9	.63–3.3	1.6	1.8	.40–1.9	.67	.90	35	70	32–66	50	51	166–330	190	228	J. E. Moore (1961); Schoff and Moore (1964).
IIA-3	Hills west of Oasis Valley.	Minor recharge area; ground water perched in tuff aquitard sampled.	5	.48–1.4	.72	.88	2.5–3.3	2.8	2.8	1.9–2.5	2.3	2.2	.91–1.8	1.1	1.2	20	68	52–55	54 (2)	54	171–266	224	217	Malmberg and Eakin (1962).
IIB	Emigrant Valley	Hydraulically closed basin with minor discharge to east. Water sampled from valley-fill and tuff aquifers(?) and aquitards.	3	.39–1.0	.42	.60	2.5–4.0	3.2	3.2	2.8–3.6	2.9	3.0	.58–.66	.62	.62	11	83	77–86	85	83	268–310	279	286	J. E. Moore (1961); Schoff and Moore (1964); U.S. Geol. Survey files, Denver, Colo.
IIC	Yucca Flat	Ground water semiperched in valley-fill and tuff aquifers and aquitards above underlying lower carbonate aquifer; only Cenozoic strata sampled.	5	.08–2.0	1.1	1.0	1.9–4.0	3.4	3.1	2.5–3.4	3.2(4)	3.1	.50–2.3	.62	1.1	24	84	61–107	74	78	274–370	296	317	Do.
IID	Frenchman Flat	Ground water semiperched in valley-fill and tuff aquifers and aquitards above underlying lower carbonate aquifer; only Cenozoic strata sampled.	3	.15–.52	.16	.28	4.5–7.2	5.7	5.8	2.9–6.3	4.9	4.7	.77–1.8	.83	1.1	3	86	55–60	56	57	337–451	369	386	Do.
IIE	Jackass Flats	Ground water in welded-tuff aquifer; water is discharged southward into Amargosa Desert.	3	.88–5.3	.88	2.4	1.9–7.0	2.2	3.7	1.7–2.1	2.0	1.9	.68–10	.72	4.1	29	74	55–67	58	60	211–886	236	444	Do.
IIF	Pahute Mesa	Ground water in tuff and rhyolite aquifers and aquitards in Silent Canyon caldera.	10	.02–2	.4	.7	1.3–6.5	2.8	3.5	1.1–5.2	2.2	2.3	.17–6.0	.94	1.7	10	71	41–50	44	45	117–583	242	297	U.S. Geol. Survey files, Denver, Colo.
IIG	Oasis Valley	Major discharge area for water in welded-tuff aquifer of Oasis Valley–Fortymile Canyon ground-water basin.	17	.28–3.8	1.4	1.5	3.8–9.8	5.5	6.1	2.6–8.7	4.5	4.7	1.6–5.9	2.2	2.7	20	67	54–68	65 (3)	62	330–1,071	532	580	Malmberg and Eakin (1962).
Calcium magnesium sodium bicarbonate facies																	**Calcium magnesium sodium bicarbonate facies — Continued**							
IIIA	Ash Meadows	Principal discharge area for water in lower carbonate aquifer of Ash Meadows ground-water basin.	6	3.5–4.2	4.0	3.9	3.1–4.8	3.8	3.8	5.0–5.2	5.0	5.0	2.2–3.1	2.2	2.5	51	70	20–33	22	24	413–500	420	441	Walker and Eakin (1963); Schoff and Moore (1964); U.S. Geol. Survey files, Denver, Colo.
IIIB	East-central Amargosa Desert.	Area of upward leakage of water from lower carbonate aquifer into valley-fill aquifer.	3	3.2–3.6	3.5	3.4	2.8–5.6	3.3	3.9	3.4–5.7	4.5	4.5	1.3–5.0	1.9	2.7	51	70	18–20	18	19	342–548	372	421	Do.
IIIC	Eastern Nevada Test Site[4].	Area of interbasin movement of ground water through the lower carbonate aquifer.	6	3.1–5.9	4.2	4.3	1.7–5.9	3.6	3.7	4.2–8.6	5.0	5.5	1.6–4.1	2.4	2.4	54	68	13–40	27	26	323–606	437	455	J. E. Moore (1961); Schoff and Moore (1964); U.S. Geol. Survey Files, Denver, Colo.
(5)																								
Sodium sulfate bicarbonate facies																	**Sodium sulfate bicarbonate facies — Continued**							
VI	Furnace Creek Wash–Nevares Springs area. Death Valley.	Major discharge area for water in lower carbonate aquifer.	3	3.3–3.9	3.4	3.5	6.3–7.2	7.0	6.9	5.2–5.8	5.7	5.6	4.5–4.6	4.6	4.6	32	56	---	25 (1)		616–716	625	652	Pistrang and Kunkel (1964).

[1] Number in parentheses after select constituents indicates number of samples when less than shown in number of samples column.
[2] Excludes Grapevine Spring, in mineralized zone in northwest Spring Mountains.
[3] Excludes analyses of water from wells less than 100 ft deep in western Pahrump and Stewart Valleys; such wells are principally along periphery of playas.
[4] Excludes 3 wells tapping the lower carbonate aquifer in northwestern Yucca Flat. The dissolved-solids content of 2 of those wells (87-62 and 88-66) is abnormally low. This property and the hydrogeologic setting of the wells suggest only local recharge; the third well (84-67) contains water apparently derived only from tuff.
[5] Data for north-central and central Amargosa Desert (area IV) and for "wet" playas (area V) omitted because hydrogeologic setting of these areas precludes meaningful statistical summary; see text discussion.

TABLE II.E-1

from perched springs in the Spring Mountains, has a lower mean concentration of sulfate plus chloride (0.36 meq/L versus 0.50 meq/L at Rainier Mesa). In fact, the mean values for 12 of the 17 sets equal or exceed the highest (1.1 meq/L) determined for the 24 samples comprising the Rainier Mesa set.

Sulfate concentrations are reported separately from chloride throughout the area of interest: at Rainier Mesa by White et al. (1980); at Pahute Mesa by Blankennagel and Weir (1973); at Yucca Mountain by Benson and McKinley (1985); at Oasis Valley by White (1979); and in the Ash Meadows discharge area by Dudley and Larson (1976). Sulfate is a persistent constituent throughout the region, commonly representing 10 to 30 percent of the total anions. That "sulfate has never been reported in the rocks of Rainier Mesa..." (manuscript Page 4-7, quoting Russell, 1987, without citation) is meaningless unless accompanied by a demonstration that is has been sought by appropriate analyses. One reviewer states that several volcanological studies since White et al. (1980) indicate that volcanic glasses are a primary source of sulfur, chloride, and fluoride, citing Devine et al., (1984). This comment and several others point out that sulfur is readily oxidized to sulfate in the vadose zone of volcanic terranes.

Differences between the chemistry of water in fractures and that in the interstices is presented in the manuscript as being highly significant and strongly suggestive of a hydrotectonic origin for the interstitial water. In addition to sulfate, most other constituents occur in greater concentrations in interstitial water than in water seeping from faults and fractures. The manuscript recommendations (Section 5.2) reinforce the perceived significance, calling for special attention to these differences, though without guidance as to the specific constituents that might be diagnostic of hydrotectonic mounding.

The significance of the observed chemical differences between fracture and interstitial waters was challenged in a large number of comments. Reviewers agreed that the differences are commonly recognized but that they result from the longer times and larger reactive surface areas available to water moving slowly through the interstices, as compared with those available to water moving more rapidly through fractures. White et al. (1980) specifically address the kinetic processes related to compositions of fracture water and interstitial water at Rainier Mesa, although they did consider sulfate to be problematical as discussed above.

The proposed relict mound at Rainier Mesa meets the hydraulic and thermal criteria for perching of either infiltrating or tectonically injected waters. The chemical characteristics are consistent with infiltrating water according to White et al. (1980), as supplemented in the case of sulfate by reviewers comments and citations. In contrast, no specific deep source of water that is "affiliated" chemically with the interstitial waters has been proposed.

d. **<u>Greenwater Range</u>**

In Section 4.8 of the manuscript, an implied contemporary mound is mentioned within the context of geologic evidence for paleodischarge. Czarnecki (1987) presented potentiometric and thermal information from mineral-exploration boreholes in the area of the Greenwater Range that indicates the presence of a groundwater divide, hence a mound, between the southern Amargosa Desert and Death Valley. The draft manuscript presents only two possible explanations, locally derived contemporary recharge or tectonic factors, discounting the first because of the paucity of annual precipitation in the area.

The limited data presently available do not include water chemistry. However, water levels in the holes stand as high as 875 m, or 265 m above the potentiometric level in the southern Amargosa Desert. Water temperature substantially exceed 40°C, reaching 70°C at a depth of 425 m in one hole. Czarnecki (1987) interprets the convex-upward shapes of the temperature profiles to indicate upward flow. He speculates that upward mounding along faults in the Greenwater Range and, though subsurface data are lacking, probably also beneath the Funeral Range provide the source for much of the spring flow in Death Valley. Winograd and Thordarson (1975) proposed underflow beneath the Amargosa Desert as the source for the springs in Furnace Creek Wash - Nevares Springs area, although they proposed mixing with water typical of Oasis Valley to account for the sodium and sulfate in the Death Valley spring flows.

Assuming eventual confirmation of the present data, the potentiometric and thermal criteria for active mounding by upwelling water are satisfied, but the causative mechanism for the upward flow remains unknown. Czarnecki (1987) proposed three possible mechanisms, which could act in concert: (1) locally derived modern recharge; (2) locally derived paleorecharge, not yet completely dissipated; and (3) deep flowpaths from remote areas of recharge and high head, such as the Spring Mountains. The last mechanism would be analogous to the Devils Hole mound described previously in this section. Some members of the committee suggest that a fourth mechanism be added to this list: the mound could be caused by active, as yet undefined, tectonic process(es). This suggestion stems from the fact that the Greenwater Range is within or adjacent to the most active extensional province (Death Valley) on the continent and is also close to evidence of young basalt flows and igneous intrusives.

Additional work in the Greenwater Range area is planned in order to better define the discharge from the groundwater subbasin that includes the Yucca Mountain area. Given the distance from Yucca Mountain, however, the study is not presently planned to be sufficiently comprehensive to provide for determining the actual source or physical cause of the upwelling.

3. **SUMMARY OF MOUNDING**

The occurrence within the region of either active or relict hydrotectonic mounds is an expected consequence of the conceptual model presented in the manuscript. However, the criteria expressed for their recognition are vague and non-specific. The hydraulic and thermal criteria for relict mounding are equally diagnostic of perched infiltrating waters. Those that might be diagnostic of an active mound probably are met in the Greenwater Range, which appears to be analogous to the Devils Hole area, where hydrogeologic factors argue strongly for recharge-driven discharge from the regional carbonate aquifer.

Three areas of mounding are proposed in Section 4.2 of the manuscript. The first, near Beatty, is presented in the most positive and conclusive terms, but it is based on sample altitudes that are erroneously stated and inferred to be supported by chemical and thermal data that are not anomalous within the setting. The second, the Skull Mountain area, does not meet the hydraulic or thermal criteria for active mounding, as the manuscript implies, and the chemical data, although sparse, seem to preclude both active and relict mounding. The third area, Rainier Mesa, is predicated to be a relict mound on the basis of chemical characteristics that are thoroughly unconvincing but are consistent with perching of infiltrating water. In each of the three cases, data that conflict with the hypothesized mounding are not presented to the reader although they are contained in the sources that the manuscript cites.

F. **POTENTIOMETRIC AND THERMAL GRADIENTS**

The manuscript indicates that some local features of the groundwater flow system and the thermal regime in the vicinity of Yucca Mountain and the Nevada Test Site are such strong indicators of the operation of coupled processes in this system that they can be considered diagnostic for the presence of a deforming fractured medium. Broad regional aspects of the potentiometric and thermal fields have been discussed previously. More detailed descriptions of selected localities and observations in boreholes are presented in the manuscript to support the author's hypothesis that heterogeneity of heat flow at very small scales produces heterogeneities of in situ stress and, thus, of hydraulic potential at similar or even smaller scales.

These phenomena are associated in Section 3.3.3 with a "mixed" convection flow system, having strong thermal heterogeneities at its base and having an arbitrary planar "boundary" at the base of the (relatively) shallow water table containing "sources" and "sinks" of water and heat.

The manuscript states in Section 3.2.4 that one consequence of groundwater flow developed within a deforming fractured medium is a water-table configuration showing, at any particular time: (1) hydraulic mounds and sinks; (2) areas with a relatively steeply sloping water table; and (3) areas with a relatively flat water table. During the deformational period, the vertical profile of hydraulic gradient will vary with the changing depth of the surface of "limit equilibrium" due to stress changes. Above this surface, fractures are postulated to be dilated in the shear mode, and the high fracture permeability results in a hydrostatic profile, i.e., there is no hydraulic gradient in the vertical direction. Beneath the surface of limit equilibrium, the conditions for shear failure and dilation have not been satisfied and permeability remains small; hydraulic potential can change only slowly in response to changing potentials above the surface of limit equilibrium. The author postulates that this will cause: (1) hydraulic potential at depth to be greater than hydrostatic, as calculated from a declining water table ("overpressure"); or (2) hydraulic potential at depth to be less than hydrostatic, as calculated from a rising water table ("underpressure"). Thermal criteria for recognizing the deforming medium are less explicit in the manuscript, consisting of "strong gradients", whether lateral or vertical. In Section 3.3.5, the author adds differences in the chemical composition of groundwater to the set of criteria.

The author states on Page 4-11 that vertical gradients of hydraulic potential are "far too often ignored". His ensuing discussion and the data contained in his citations demonstrate that vertical potentiometry has been an important consideration during more than three decades of hydrologic data collection associated with the Nevada Test Site. These data have been used extensively for interpretive syntheses of hydrogeologic controls on groundwater flow in the southern Great Basin. Although the presence of the lower carbonate aquifer at depth complicates the relationship, fracture permeability is generally presumed (e.g., Blankennagel and Weir, 1973) to decrease with depth in response to the increasing lithostatic load and as a result of secondary mineralization. The only apparent way to test the relative importance of hydrogeologic controls and stress controls on fracture permeability would be to observe hydrologic changes, or lack thereof, attending stress changes caused by seismic or aseismic fault movements.

The connection of water table configuration and vertical differences in hydraulic potential with heterogeneities in stress distribution and heat flow is not explicitly shown either conceptually or mathematically; it is merely stated to exist as a consequence of the model. A hydrologically naive reader could be left with the impression that conventional hydrogeology fails to account for variations of head with depth or a water table surface more complex than a tilted plane; such a reader would perhaps believe that this failure forced the author to invoke mechanisms more complex than gravity-driven flow to explain the observed water table and potentiometric data. If an entire area were underlain by a homogeneous material having uniform porosity and permeability, containing no faults or other discontinuities, and complex configurations of the hydraulic and thermal fields were observed, then one would be compelled to seek causes for these observations other than the variations in "durable" properties of the system. In the reviewers' opinion, there are already more than enough degrees of freedom arising from incomplete knowledge of detailed structure, stratigraphy, lithology, and associated hydrologic parameters of the Yucca Mountain area to account for all observed hydrologic data. Because the effects of heterogeneous stress and thermal gradients must be superimposed on conventional geohydrologic controls of groundwater flow, a rigorous treatment of the author's conceptual model would necessarily introduce even more parameters. Ignoring the variability of conventional properties in a geologically diverse setting in favor of considering variations in second-order driving forces appeared to the reviewers to be an unnecessary complication which is difficult, if not impossible, to test.

Three areas (Beatty, Skull Mountain, and the Greenwater Range) of postulated active groundwater mounding and one (Rainier Mesa) of postulated former mounding were discussed in a previous section of this review. Four additional areas of large or variable hydraulic and thermal gradients are described in varying detail in the manuscript. The potentiometric, thermal, and chemical characteristics of these other areas that the author cites as diagnostic, or possibly diagnostic, of a deforming fractured medium are reviewed and evaluated below.

1. YUCCA FLAT

Plate 4.3-6 shows a map and cross section of northernmost Yucca Flat and western Emigrant Valley. It receives little discussion in the manuscript other than noting that large hydraulic gradients are evident, which is true. The largest gradient (~1300 ft per mi) shown occurs at the north end of Yucca Flat, between two test holes (89-68 and 88-67a) located on opposite sides of the Yucca Fault (a possible hydraulic barrier).

As interpreted by Winograd and Thordarson (1975), western Emigrant Valley is underlain by a structurally elevated block of Precambrian and Cambrian quartzites and argillites comprising the lower clastic aquitard, the top of which they consider to be the effective base of active groundwater flow throughout the region. Because of its very low permeability, it is saturated nearly to the surface (where it outcrops) or to its upper limit (where it subcrops below more permeable materials). The water level in hole 89-68 reflects the potentiometric level at the edge of this elevated aquitard, where the level is declining steeply into much more permeable rocks beneath Yucca Flat. Hole 88-67a penetrates the highly transmissive lower carbonate aquifer, with a potentiometric level that is compatible with that in this unit throughout Yucca Flat and downgradient to the discharge area in Ash Meadows. These hydrologic details, which seem to be important controls on groundwater flow, indicate why the reviewers took exception with the author's treatment of the suballuvial rocks as a single homogeneous unit.

Beneath most of Yucca Flat, the top of the lower carbonate aquifer is beneath its potentiometric altitude; i.e., it is an artesian aquifer. The actual water table is in the overlying Cenozoic tuffs and sediments (Winograd and Thordarson, 1975; Doty and Thordarson, 1983). The water table altitude is higher than the potentiometric level in the carbonates, and the potential or head decreases with depth as water seeps downward, losing potential energy in the process. The manuscript cites examples in which the head declined during the drilling of exploratory holes. This, according to the author, is an indication of underpressure. The difficulty with this interpretation is that the underpressure was represented to occur because the rocks at depth were unable to adjust potentiometrically to the decline of hydrostatic pressure above the surface of limit equilibrium. The rocks with the lowest heads and the highest transmissivities in not only Yucca Flat, but also throughout the southern Great Basin, are those of the lower carbonate aquifer, which recovers very quickly from the effects of hydraulic stresses.

Where they are not disrupted by faults, extensive fracturing, or dissolution, the dolomites and limestones of the aquifer have rather low permeability, high density, and large thermal conductivity. Permeable zones are associated commonly with identified faults (e.g., drill hole UE25p-#1) (Carr et al., 1986; Craig and Robison, 1984). Within the region, highly permeable zones of dissolution have been penetrated in these carbonates, though infrequently (Winograd and Thordarson, 1975). They seemingly are distributed capriciously, probably controlled by highly localized details of lithology, structure, and geometric constraints on the groundwater system, both present and past. The absence of Mesozoic rocks (except intrusives) in the vicinity (Winograd and Thordarson, 1975) indicates long exposure of the Paleozoic section at the surface, possibly during the Mesozoic Era, but certainly in Laramide time (Late Cretaceous and early Tertiary). Karstic features that could not form in the deep subsurface in the present geochemical regime probably are broadly distributed throughout the area but comprise, both areally and volumetrically, very minor parts of the aquifer, as evidenced by the rarity with which open cavernous zones have been found during drilling. Most penetrations of the lower carbonate aquifer in the southern Great Basin have encountered large transmissivities, whereas very few have failed to intersect permeable zones. Hence, closely-spaced fractures (with at most minor solution enlargement) must be the cause of the areally rather uniformly high transmissivity (Winograd and Thordarson, 1975). Whether enhanced by minor solution enlargement or by slight displacement as they formed during Mesozoic thrust faulting, the fractures provide a very durable transmissivity to the lower carbonate aquifer, as evidenced by its typically large productivity at all depths.

Some holes, however, penetrate significant thicknesses of slightly permeable carbonates before intersecting a transmissive zone (Winograd and Thordarson, 1976). The overlying less permeable carbonates exhibit similar behavior to the higher Tertiary section; i.e., the head continues to decrease downward.

In the reviewers' opinion, low permeability is a much more likely explanation for the downward decline of head in the upper part of the carbonate section in drill hole 83-69a than the author's position (Pages 4-13 and 4-14) that the underpressure is not hydrogeologically controlled.

The author also considers the low and fairly uniform distributions of subsurface temperature and heat flow at Yucca Flat to be evidence of a deep surface of limit equilibrium. In section II.C of this review, Yucca Flat was shown to be within the regional heat-flow low termed the Eureka Low by Sass et al. (1971). Their interpretation (increasingly supported by evidence gathered since 1971) is that heat is being removed from this area by lateral flow in the carbonate aquifer, which homogenizes temperature as well as head. The manuscript offers no cogent reasons to reject this interpretation.

Finally, the author presents a generalized map of the water table beneath Yucca Flat (Plate 4.3-7), taken from a field-trip guidebook edited by Corchary and Dinwiddie (1976). The author cites an apparent abundance of control data (resulting from extensive drilling at Yucca Flat for nuclear testing) used for the water-table contours shown on the map as strong evidence for the existence of the hydraulic mounds and sinks he envisions as consequences of his conceptual model. The map in question is not discussed in the published or written record (other than in the manuscript under review). Therefore, the following explanation is provided by the senior editor of this review, who prepared the map.

> "This map is both highly interpretive and generalized; it was intended only as a basis for oral discussion on field trips or in meetings. I prepared the map from a larger-scale, more detailed version that I developed in 1973 or 1974. The map was periodically updated by G. C. Doty and William Thordarson, as new data were obtained, in support of selecting sites for the ongoing program of underground nuclear testing. The principal purpose of the map was to predict as accurately as possible the depth to the water table so that nuclear tests could be sited in a dry emplacement hole, whether by staying above the water table or, if necessary, by installation of a water-tight liner; in the latter case, the hydraulic information was used for liner design.
>
> "In the early 1970's, it became evident that compaction of the rocks around underground explosions (UNE's) had caused high potentiometric levels that persisted for apparently long times. R. K. Blankennagel first attempted to identify individual mounds, but data were insufficient to provide confidence in the intervening areas, which were still to be used for siting new UNE's. Consequently, I generalized the water-table configuration conservatively, i.e., to err on the side of predicting a minimum depth to water. It was not clear whether the water table was actually elevated or whether only confined overpressures were responsible for the composite heads that were observed in some holes. In order to assure conservatism, my assumptions were: (1) the observed heads would be treated as though they were actual water-table rises; (2) the prevailing decrease of head with depth would be preserved in the interpretation by increasing the altitudes of observed composite levels according to the apparent degree of penetration of the saturated tuffs, assuming that the composite represented the head at the greatest depth of penetration; and (3) measurements in holes that preceded nearby UNE's,

and that were no longer available for remeasurement, were treated only as water-table minima; i.e., they could be higher due to the effects of the subsequent testing. Temporarily deep water levels in rubble chimneys were ignored.

"Despite the large number of holes in northern Yucca Flat, hydrologic data were obtained in very few after the initial exploration of the 1950s and 1960s. Consequently, the data reported by Winograd and Thordarson (1975), which terminate about 1965, represent much of the data base; exploratory holes were rarely drilled in the increasingly well known areas used for nuclear testing, and the large-diameter emplacement holes that penetrated the water table were lined immediately after reaching design depth. Much of the additional data was opportunistically obtained when anomalous heads were encountered; in some cases, the water rose above the tops of the liners. As noted in the third assumption above, the data also vary in time of collection, but within a period of changing levels. The entire data set that was deemed to be useful as of about 1980-1982 is portrayed on the only published version of the periodically updated map (Doty and Thordarson, 1983).

"The large mound portrayed along the Yucca Fault in northern Yucca Flat is in the area of most intense testing and the area for which conservatism was most necessary. As I recall, the presence of the potentiometric mound was based on about five data points. Centering its axis on the fault was purely speculative and was intended to show the possibility that observed displacements associated with UNE's might have increased fluid pressure attending stress increase in the normal-fault zone. There were no data with which to evaluate this speculation.

"The queried sink along the Yucca Fault was based on a single datum of 2401 feet somewhat east of the fault that suggested a slight depression of the water table. The inclusion of a 2400-ft contour and a small area of <2400 ft along the fault was intended to suggest the possibility that the fault zone could be a preferred vertical pathway for flow from the Cenozoic rocks to the carbonates.

"No subsurface data support the presence of the queried mound beneath the southern end of Yucca Flat. It was again entirely speculative, based on my (and others') observations of substantial storm inflow to the large 1969 crack that opened across Yucca Playa, the latest of a series of such cracks which, according to their morphology, formed successively southward. They were interpreted by Carr (1974) to be tectonic in origin, suggesting -- as did the observed inflow rates, which I estimated to be perhaps a few hundred acre-feet per year -- that the inflow reached the water table.

"The existence of the trough in the water-table configuration of northwestern Yucca Flat is reasonably well controlled by data. It occurs where the lower carbonate aquifer is structurally high, which is confirmed both by a gravitational high and by drilling."

The discussion above shows that the map in question should not be regarded as a well controlled portrayal of the water table beneath Yucca Flat, and also suggests that underground nuclear explosions must be added to the author's list of man's activities that perturb the hydrologic system.

2. PAHUTE MESA

a. Hydraulic Characteristics

Data for Pahute Mesa wells from Blankennagel and Weir (1973) are shown on a map on Plate 4.4.1, presented in tabular form on Plate 4.4.2, and idealized in two schematic plots of pore pressure versus depth on Plate 4.4.3, with one plot for the western portion of the mesa and the other for the eastern portion.

From Plate 4.4.2, the author concludes that, in boreholes where the head decreases with depth, composite water levels represent the head in the deeper, underpressured zones and that, in the other wells, composite water levels do not represent the head in the deeper, overpressured zones. In the latter case, he states that flow upward from the deeper zones "must enter the formation [at shallower depths] without noticeably raising the fluid level in the borehole," and then concludes that "The height of the water column **must be controlled by the in situ stress present in the fractured medium**" [emphasis added].

Intra-borehole flow is common where a borehole penetrates units with differing heads. A composite fluid level for a system with two zones that communicate only through a borehole would be expected initially to lie somewhere between the heads of the individual zones, and closer to the head of the zone of higher transmissivity. The long-time behavior depends upon whether the two zones are of finite extent (limited fracture or pore volumes connected to the borehole) or effectively infinite. If both zones are finite, after a sufficiently long time they will reach equilibrium at a fluid level that is a storativity-weighted average of the two initial heads. If both zones are infinite, the fluid level in the well asymptotically approaches a transmissivity-weighted average. Finally, if one zone is finite and the other is infinite, the final fluid level will correspond to the initial head in the infinite zone. The situation is more complex in the real world, such as Pahute Mesa, where several permeable zones of differing heads occur in the same borehole and where lateral changes of transmissivity preclude the clear-cut idealization of "finite" or "infinite." However, the point is that composite fluid levels depend upon many details of the hydrogeology, and there is more than "only one logical explanation."

Table II.F-1 is a somewhat reorganized version of the Blankennagel and Weir (1973) data, reproduced in the manuscript as Plate 4.4-1. Directions of hydraulic gradient between pairs of tested zones have been added (arrows), as have "pointers" (<) at intervals toward which flow converges both downhole and uphole. A similar scheme is basic to the structure of Figure II.F-1. The potentiometric levels of the individual test zones are represented by the width, increasing to the right, of rectangles of which the top and bottom define the vertical interval that was isolated. The open-hole water level, representing the composite head, is shown by a dashed vertical line referenced to the potentiometric scale (i.e., increasing head to the right). The

BOREHOLE	ISOLATED INTERVAL (Feet)	DEPTH TO WATER (Feet)	GRADIENT DIRECTION	PERMEABLE ZONES (Feet)	OPEN-HOLE WATER LEVEL
UE19c	2319 - 2874 2884 - 3284 4033 - 4231	2319 ? 2348 2360	↓ ↓	3050 - 3075	2345
UE19d	2500 - 3483 3472 - 3852 3844 - 4042 4626 - 4784 4810 - 4986 5823 - 6583	2177 2186 2178 2180 2200 2210	↓ < ↑ ↓ ↓ ↓	3300 - 3350	2177
UE19e	2619 - 2778 4802 - 6004	2232 2253	↓	2650 - 2690 4970 - 4990	2240
UE19fs	2750 - 3218 3520 - 3838 4146 - 4480	2302 2304 2309	↓ ↓	2880 - 3160	2305
UE19gs	2802 - 2970 4636 - 4834 6920 - 7118	2043 2050 2049	< ↓ ↑	2940 - 2970 4786 - 4790	2045
UE19i	2910 - 3068 3460 - 3618 4100 - 4258	2220 2258 2218	↓ < ↑	3400 - 3470 3750 - 3765	2258
UE20d	2578 - 2776 4118 - 4316	2078 2018	↑	2578 - 2730	2075

BOREHOLE	ISOLATED INTERVAL (Feet)	DEPTH TO WATER (Feet)	GRADIENT DIRECTION	PERMEABLE ZONES (Feet)	OPEN-HOLE WATER LEVEL
U20a-2	2067 - 2608 2492 - 2682 2895 - 3085 3090 - 3280 3648 - 3838 4048 - 4238 4355 - 4500	2064 2066 2065 2064 2042 2051 2033	↓ < ↑ ↑ ↑ < ↓ ↑	2400 ┐ └ 2682 2895 - 3085 3648 - 3838	2066
U20e-1	2774 - 2972 3480 - 3678 4020 - 4218 4540 - 6395	1828 1835 1828 1820	↓ < ↑ ↑	3550 - 3660	1822
UE20f	2598 - 2796 3150 - 3348 3338 - 3536 4350 - 5249	1946 1988 1954 1857	↓ < ↑ ↑	3150 - 3660 4568 - 4766	1954
Deepened	4490 - 13,686	≤1772	↑	(4568 - 4766)	1772
UE20h	2575 - 2743 2741 - 3210 3350 - 3518 3705 - 3873 3892 - 4060 4070 - 4238	2111 2116 2111 2114 2116 2117	↓ < ↑ ↓ ↓ ↓	3042 - 3170 4040 - 4060	2116 ┐ ? 2116 ┘
UE20j	1858 - 2056 2051 - 2249 2253 - 2461 2670 - 2868 2957 - 3155 3359 - 3832 4023 - 5690	1245 1247 1249 1261 1270 1273 1264	↓ ↓ ↓ ↓ ↓ < ↑	2060 - 2150 2957 ┐ └ 3557	1270

TBLIIG-1/4-24-89

Table II.F-1. Reorganized hydraulic-test data from deep drillholes at Pahute Mesa, Nevada Test Site. Adapted from Blankennagel and Weir, 1973, Table 7. (Original table also reproduced as Plate 4.4-2 by Szymanski, Nov., 1987 draft.)

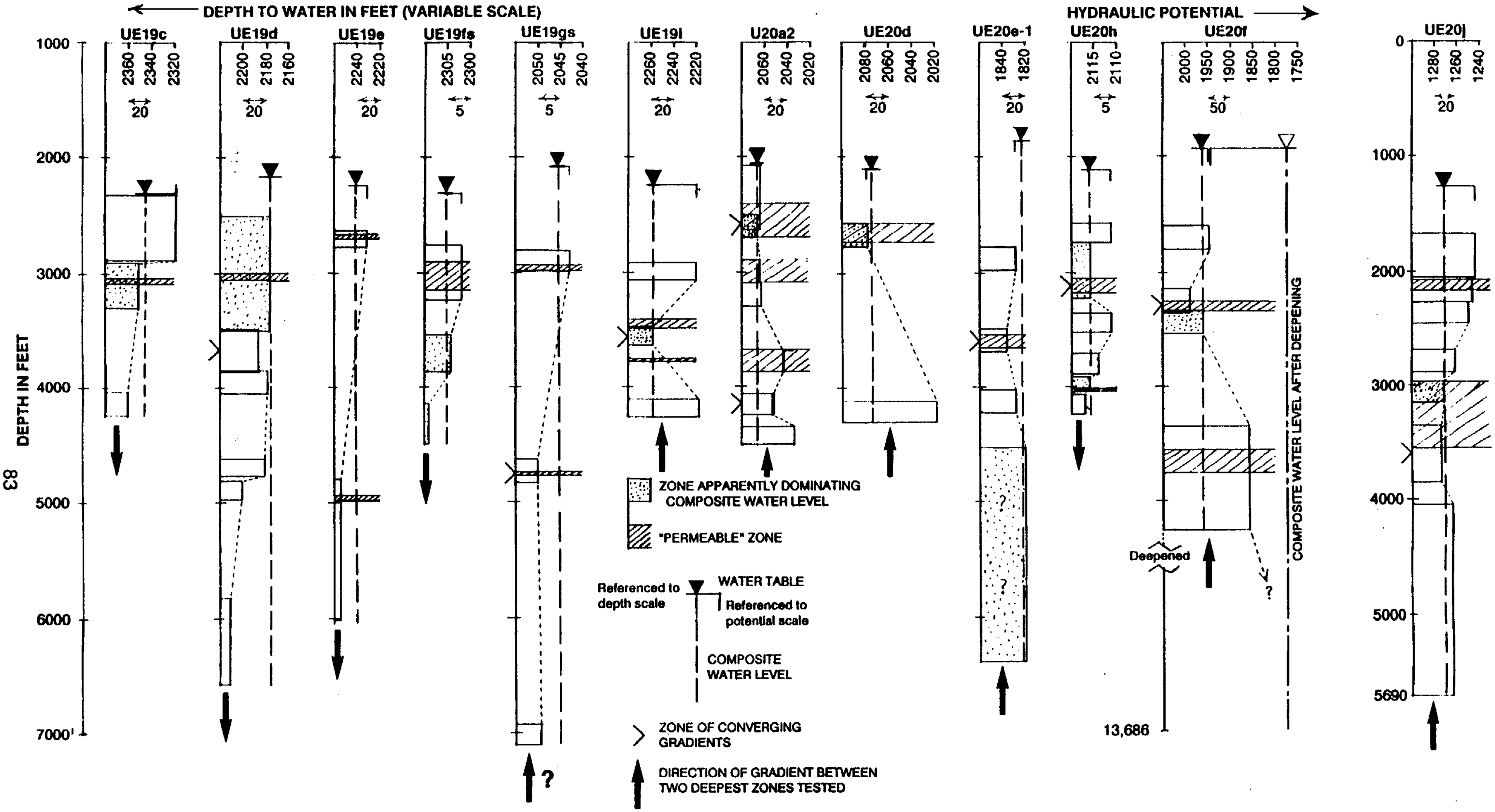

Figure II.F-1. Hydraulic potentials plotted against depths of isolated intervals, composite open-hole water levels, and identified permeable zone for deep drillholes at Pahute Mesa, Nevada Test Site. Drawn from data in Blankennagel and Weir, 1973, Table 7.

apparent water table, estimated as the head in the shallowest zone tested, is referenced to the depth scale by a horizontal line emphasized with a darkened triangle and is referenced to the potentiometric scale with a short vertical line. Study of Figure II.F-1 is arduous but fruitful. It shows:

(1) Only UE19c and UE19fs, among the ten holes with water levels measured in three or more packed-off intervals, have a consistent direction (downward in both wells) of the vertical hydraulic gradient. The potential for both uphole and downhole flow occurs in each of the other eight holes.

(2) Composite water levels (not corrected for possible effects of temperature on the relative density of water) approach those of identified permeable intervals or lie between those of multiple permeable intervals, as is consistent with the tutorial discussion above. The single exception is UE20e-1, where the deep zone (4540 to 6395 ft) that dominates the open-hole level was not explicitly identified by Blankennagel and Weir (1973) as being "permeable."

(3) Composite heads in areas of downward hydraulic gradient are not dominated by the deeper underpressured zones unless the deeper zones are more permeable. UE20h is the only example of the exception, and it is ambiguous because the composite level is common to the heads in two intervals that are separated by two other intervals with higher heads.

(4) Similarly, composite heads in areas of upward hydraulic gradient generally do reflect the influence of higher heads in the deeper zones. Where they do not, it is the result of higher permeability in the shallower zones. After deepening of hole UE20f, the composite water level rose almost 200 ft and then was clearly dominated by deeper zones.

Blankennagel and Weir (1973) attribute the decreasing heads in the eastern part of the area principally to the relatively great competence and low compressibility (as compared with the nonwelded tuffs) of the thick rhyolite lavas that dominate the geologic section. They postulate that the mechanical competence of the rhyolite and of densely welded tuffs provides the capability to maintain open, permeable fractures at considerable depth despite high lithostatic loads. They further describe the effects of the hydrogeologic framework, as summarized below.

> In the central part of the area, the rhyolites and welded tuffs are irregularly distributed and occur mainly above the water table. In the southwestern part, regionally downgradient, they occur only in the upper part of the saturated zone. In both areas, the deeper section is dominated by nonwelded tuffs, which Blankennagel and Weir (1973) judge to be both less fractured and less able to maintain fracture permeability under high lithostatic loads. Consequently, the permeable section available for flow thins and becomes shallower in the direction of the regional water-table gradient, that is, from east-northeast to west-southwest. As water seeps downward in the east to utilize the thick permeable section, head loss occurs along the downward flow paths. Beneath the central and southwestern zones, however, the flowpaths converge upward toward the permeable zones with an attendant upward loss of head.

Examination of the borehole test data shows that local and complex responses to the distribution of permeability are superimposed on this general pattern of flow, providing a strong contrast with the idealized distribution of hydraulic potential depicted on Plate 4.4-3.

b. Hydrochemistry

On Page 4-13, the manuscript indicates that water analyses tabulated on Plates 4.4-6 and 4.4-7 show that "the content of sulfate and chloride is noticeably increased where the upward vertical components of flow are observed." However, borehole UE19c has relatively high concentrations of both sulfate and chloride, but it is in an area where head decreases with depth. Borehole UE19i is in an area of increasing head with depth; its sulfate concentration is high, but its chloride concentration is very low. Also in areas of increasing head with depth, both U20a2 and UE20f have low concentrations of both sulfate and chloride. Again, a detailed examination of the data reveals little support for the plausibility of the proposed conceptual model.

c. Relationship of Temperature to Hydraulics

The temperature profiles in two holes, UE19gs and UE20f, are identified by the author as showing "distinct sharp increase[s]...of the geothermal gradient," reflecting his claimed previous demonstration (by the hydraulic and chemical data discussed above) of a deforming fractured medium. The profiles, from Sass and Lachenbruch (1982), are shown on Plate 4.6.2-2, and they are indeed expressive.

i. Exploratory Hole UE20f

In UE20f, upward from the deepest part of the logged interval (about 12,270 ft) the temperature decreases linearly from 121°C to about 97°C at 9840 ft, with a gradient of 37°C/km. About the same average gradient occurs up to a depth of 8700 ft, but there are significant departures from linearity. Upward from 8700 ft, there is a sharp reduction of gradient that is gradually recovered, producing an upward convexity in the profile, up to 4760 ft, where the temperature is still relatively high at 65°C. The temperature decreases sharply from 4760 ft to 4600 ft, where it is 46°C. From there up to the composite water level at 1772 ft, the profile is only slightly irregular with an average gradient of 26°C/km.

The author does not state whether the "distinct increase" is intended to apply to the sharp increase (downward) of temperature between 4600 and 4760 ft, or whether it is to apply to the difference between the gradients in the two widely separated linear segments of the profile. Recall from the earlier discussion of the geothermal framework that heat flows of 2 to 2.5 HFU and <1 HFU were reported by Sass and Lachenbruch (1982) for the deeper and shallower segments, respectively.

A hydrologic interpretation is that there are probably no significant differences of head in the rocks below a depth of 9840 ft and very little difference below 8700 ft. The local base of the geohydrosphere seems to be at about 9840 ft. In a narrow zone at about 8700 ft, flow enters the borehole driven by a head that is 182 ft greater than the water level that existed in the hole before it was deepened beneath 5249 ft; perhaps a few tens of feet of this difference can be attributed to the lesser density of the hot water, leaving a substantial difference of hydraulic potential to drive water up the hole. Very little loss of water from the borehole to the rock occurs until the flow reaches the interval 4600-4760 ft, where most of it is returned to the rocks. Note on Table II.F-1 that Blankennagel and Weir (1973) defined a permeable interval at 4568 to 4766 ft. After establishment of the new, higher composite level, only slight upward flow above 4600 ft was required to satisfy the acceptance capacity of the higher intervals, resulting in a nearly linear thermal gradient. This indicates that the rocks above 4600 ft have no significantly transmissive zones of great extent from the borehole. It indicates also that the near-static conditions in the borehole above 4600 ft have allowed good thermal equilibration of water in the hole with the rock, implying high confidence that the gradient used for the heat-flow calculation (<1 HFU) was either correct or slightly too large.

ii. **Exploratory Hole UE19gs**

Borehole UE19gs at first appears to be less readily explained because the data are seemingly less complete and expressive. The temperature log begins at about 6075 ft, or about 1430 ft above the drilled depth of 7506 ft. Upward to 4790 ft the profile is approximately linear, with a gradient of about 31°C/km. At the scale of Plate 4.6.2-2, the uppermost part of this segment displays a slight curvature, convex upward, that indicates cooling of about 1°C within only a few tens of feet.

On the upper part of the temperature log, the profile is approximately linear for a few hundred feet beneath the composite water level, 2045 ft. The profile begins to steepen at about 2400 ft and is somewhat irregular down to the 4790 ft depth. It appears that the 2400 to 4790 ft interval contains three zones of very small inflow to the hole that may be more evident on the original field log. However, its fundamental pattern indicates downflow in the borehole from about 2400 feet to the permeable interval identified by Blankennagel and Weir (1973) at 4786 to 4790 ft, which has the lowest head of the three zones tested. Apparently there is greater permeability above the 2940 ft depth than is indicated by the data in Blankennagel and Weir (1973). (This is not a criticism of those authors; there were limitations on the rig time that was affordable within both schedule and financial constraints.)

Returning to the lower segment of the temperature log, a projection of the linear gradient to the drilled depth (7506 ft) results in a predicted temperature of about 66°C. However, Blankennagel and Weir (1973, Table 8) report that the bottom-hole temperature was measured as 61.6°C on May 4, 1965. This indicates that, if the log had been run to total depth, it would have displayed convex-upward curvature, the recognition pattern for uphole flow of sufficient intensity to prevent thermal equilibrium of the water in the borehole with the adjacent rock. As heat is transferred from the upward moving water to the rock either by conduction or seepage from the hole into the rock, the temperature differential decreases, with a corresponding decrease of the curvature of the profile. After enough heat is lost, the temperature profile becomes apparently linear, appearing to show only conductive heat flow. Because the upper end of the segment is displaced only about 1°C warmer than actual, whereas the projection of the linear segment is displaced 4.4°C warmer than actual, the apparent gradient is larger than that in the rock by about 30 percent.

It must be recognized that this analysis is based on a very small scale representation of the actual field log, and it may be found to be incorrect upon more detailed reevaluation. Furthermore, Blankennagel and Weir (1973, Table 8 and Figure 10) include UE19gs in their class of boreholes for which head decreases with depth, apparently and reasonably judging that the 1-ft difference between the heads in the deepest and intermediate zones was not significant with respect to the accuracy of measurement. The thermal data indicate that it may, in fact, have been significant. The very small difference in the heads is consistent with the small uphole flow inferred from the temperature log.

iii. UE20f Revisited

The foregoing analysis of well UE19gs raises the possibility that the linear profile below 9840 feet in UE20f may not indicate the conductive thermal gradient in the rocks, because the log begins 1416 feet above the bottom of the hole. Blankennagel and Weir (1973) did not report an actual bottom-hole temperature for UE20f but, rather, show on their Table 8 the depth and temperature of the bottom of the profile determined by the temperature log. It seems unlikely that the profile would not display any upward convexity over the 2430 ft apparently linear segment, because 63 percent of the interval that could have been logged was logged, as compared with 48 percent in UE19gs. However, as the profile ascends to the 9840-ft depth, there is a slight decrease (1 to 2°C) of temperature that is reminiscent of that at 4760 ft in UE19gs. The possibility that uphole flow did occur in UE20f may explain why the range (2 to 2.5 HFU) estimated by Sass and Lachenbruch (1982) seems slightly high for the Great Basin average of 2 HFU. Re-examining the geology of this borehole and other geophysical logs, which may have reached total depth, should help to assess this possibility.

d. CALICO HILLS

In Section 3.3.1 of the manuscript, the author proposed a correlation between seismic P-wave velocity minima and evidence of volcanism and high heat flow. The correlation was tested previously in this review (Section II.C), with the conclusion that it is lacking. However, the highest apparent heat flow (3.1 HFU) that has been determined in the vicinity of the Nevada Test Site occurs at drill hole UE25a-3, in the Calico Hills, as reported by Sass et al. (1980). This hole is at the northern edge of a seismic anomaly that encompasses most of southwestern Nevada Test Site and is approximately on the -2% velocity contour, expressed as a departure from the regional average velocity. It is stated on Page 4-19 of the manuscript that "examining the depth distributions of the in situ temperature, it becomes clear that the flow field is characterized by a large degree of thermal heterogeneity. Sass and Lachenbruch, 1982, and Sass, et. al., 1980, attributed this heterogeneity to 'local groundwater circulations'. These authors, nevertheless, recognized the convective aspects of the flow system in at least one area or possibly two areas. One of these areas is around well UE-25a3 and another is situated around well PM-2, Plate 4.6.2)."

The heat-flow calculation in Sass et al. (1980) for the upper part of the hole appears to merit rather high confidence. The thermal gradient is exceptionally linear between 643 m and 705 m in altered Eleana argillite (see Plate 4.6.2-7 in the manuscript), which characteristically in the region has very low permeability. Although there are no hydrologic data from this hole, there is no reason to expect vertical flow of significance in the borehole within the argillite interval. The calculation for this zone provided the 3.1 HFU value. These authors also estimated a gradient of 45°C/km by utilizing the mean annual ground surface temperature, as estimated from an empirical relation to altitude in the area, and air temperature within the borehole, resulting in an estimated heat flow of 3.3 HFU. The reasonable agreement indicates little, if any, flow in the borehole beneath the water level and, if any, it was probably downward.

As described by Sass et al. (1980), below 705 m the hole entered a carbonate zone having a smaller thermal conductivity than the argillite, and the thermal gradient decreased. Conductive heat flow was calculated to be 1.8 HFU and, from the diagnostic upward concavity of the profile, was interpreted to be suppressed by diffused (occurring both in the borehole and in the rock) vertical downflow of 255 mm/yr. From 735 m down to the total logged depth of about 750 m, the profile is irregular though suggestive of two or more zones of flow into the hole and then downward; the lower few meters of the profile is nearly isothermal. Sass et al. (1980) tentatively attributed this to downward flow in a steeply dipping fault intersected by the hole at 746 m., implying little confidence in a calculated heat flow of ~0.8 HFU.

The carbonate unit is thought to be Unit I of the Eleana Formation (Maldonado et al., 1979), because it consists of weakly metamorphosed carbonate rocks unlike those that commonly comprise the lower carbonate aquifer. The assumption of diffused downward flow in the calculations of its rate and of the heat flow in the upper part of this unit probably is not supportable in rocks of this type. Consequently, it is judged herein that downward flow in the borehole suppressed the apparent thermal gradient throughout the carbonate section. Therefore, the heat flow in and beneath this unit is, unfortunately, indeterminate, but that in the overlying argillite appears to be well constrained in the range of 3.1 to 3.3 HFU. Three possible explanations are immediately evident:

(1) The high heat flow may prevail at greater depths. This seems unlikely as a single, isolated occurrence in the southern Great Basin, but currently available data cannot rule it out.

(2) Upward flow from much greater depth along the steeply dipping fault or other similar faults nearby could be introducing heat into the shallow crust, whether by mechanisms proposed in the manuscript or by recharge-driven hydraulic head. This is not consistent with the evidence from the thermal profile that head decreases with depth in UE25a-3, although confirming hydraulic measurements are not available.

(3) Lateral flow along principal regional pathways in carbonate rocks, controlled by geologic structure or by dissolution, could, depending on their structural altitude at any given locality, serve either as a heat sink (where the flowpath is deep) or as a heat source (where the flowpath is shallow). For such a pathway to provide a heat source in the Calico Hills requires at least one of the following: (a) The carbonate section of the Eleana Formation is areally extensive, acting as a regional aquifer. This is believed not to be the case. (b) The carbonate rocks in UE25a-3 are actually the lower carbonate aquifer, altered during the same hydrothermal event that altered the argillite and the tuffs of Calico Hills. This also is believed not to be the case. (c) The carbonate section is indeed part of the Eleana but is hydraulically well connected with the lower carbonate aquifer and is favorably situated to participate in the regional flow pattern. (d) The Eleana sequence is incomplete because it is part of a thrust plate overriding the lower carbonate aquifer, which is structurally high beneath the Calico Hills, perhaps not far below the total depth of the drill hole. Combinations are possible, such as the thrust fault providing the hydraulic communication between the Eleana carbonate and the lower carbonate aquifer.

e. <u>YUCCA MOUNTAIN</u>

There are two plates in the manuscript that show the configuration of the water table in the vicinity of central Yucca Mountain. Plate 4.4-9 is a clearer reproduction and includes the 730-m contour, which is not on Plate 4.3-5, referenced on Page 4-10. Discussion of Plate 4.3-5 in the manuscript is brief, referring only to the locally steep hydraulic gradients. Discussion of vertical hydraulic gradients is more extensive, including statements that: (1) rather large increases of head with depth occur in three of the seven holes discussed; (2) composite water levels in these three holes fail to show the influence of the higher heads at depth; and (3) in situ stress measurements in four holes fully support the conclusion that "the deformed or deforming fractured medium is involved" (Page 4-14). An idealized representation of vertical changes of head is provided on Plate 4.4-11, showing variability of gradients to a depth of about 1200 m, below which head increases toward an overpressured profile. This is a reasonable portrayal of the data from Robison (1984).

The increases of head with depth in USW H-1, USW H-3, and UE25p-1 are accurately described. Composite heads in H-1 and H-2 are essentially the same as heads in individual, shallower zones; in each of these two wells, the deepest interval tested had a significantly higher head than the composite. Reviewers attribute the higher fracture transmissivities in the shallower intervals principally to the lithostatic increase of in situ stress with depth and an attendant closure of fractures.

However, the composite level during drilling of UE25p-1 rose abruptly to the potentiometric level of the deep zone upon penetrating the contact between the Tertiary tuffs and underlying Paleozoic carbonates at a depth of about 1200 m (Craig and Robinson, 1984). It continued to be dominated by the the 23.9 m higher level during the rest of the drilling. This is a clear illustration of large permeability, because of the dominance of hydrogeologic factors, at a depth that the author considers to be beneath the surface of limit equilibrium.

The in situ stress data of Stock et al. (1985; 1986), shown in the manuscript on Plates 4.5-5 through 5.5-8, do not indicate abrupt increases of stress in the vicinity of 1200 m, and there does not seem to be a correlation between in situ stress and water-table altitude as might have been implied by the author. (The paragraph on Page 4-14 opens with discussion of composite levels in open holes, and the context of his reference to stress is not clear.) In decreasing order of water-table altitudes, as reported by Robison (1984), the approximate values of the least principal stresses, in bars as reported by Stock et al. (1985 and 1986), at 500, 1000, and 1500 m are:

Hole	Water-Table Altitude, m	Stress (bars) at Depth 500 m	1000 m	1500 m
USW G-2	1029.1	~ 65	100	~160
USW G-1	753.8	~ 30	100	~170
USW G-3	729.9	?	~ 60	~135
UE25p-1	729.9	>~50	120	200

Ue25p-1 has the greatest, and USW G-3 the lowest, magnitudes of in situ stress, but their water-table altitudes are the same. The locations where the water table is higher and where hydraulic gradients are large have similar, intermediate values of stress, but the water-table altitudes are significantly different.

The large gradients toward Yucca Mountain from the north and west (Plate 4.4-9) have not yet been explained hydrogeologically, because there are insufficient data to distinguish among several alternatives for the smaller transmissivities within, and possibly also upgradient from, the zones of large gradients. These include the following:

(1) that there is a significant change of depositional rock facies, particularly a greater tendency to develop and maintain open fractures, southward from the Timber Mountain and associated caldera complexes;
(2) that secondary alteration associated with the Miocene volcanism decreases to the south, with an attendant increase of unhealed fractures;
(3) that Miocene and later tectonism produced less fracturing to the north;
(4) that the volcanic rocks thin over a buried high of older, less permeable rocks such as the Eleana Formation (the upper clastic aquitard), which is exposed at the surface to the east in the Calico Hills;
(5) that the tuffs in the north have been intruded by igneous rocks that are not as fractured as the tuffs;
(6) that faults have interrupted the continuity of permeable zones; and
(7) that gouge and alteration minerals have formed in the fault zones.

Combinations of these factors are also possible.

The durability of the features and, hence, the effectiveness of the hydraulic barrier, after potential future faulting is a legitimate question. Site characterization activities planned to investigate this belt of large gradients are discussed in Section 8.3.1.2.3.1.2 of the Site Characterization Plan.

The author cites (on Page 4-20) the thermal profiles of Sass and Lachenbruch (1982) for boreholes USW G-1 and USW H-1 as examples of a distinct sharp increase of the geothermal gradient with depth. These profiles are shown on Plate 4.6.2-7 of the manuscript. According to the author's concept, this represents a change from conductive (i.e., in the rock only) heat flow in the poorly permeable rock beneath the surface of limit equilibrium to a combination of conductive heat flow and convective heat transport by water above the surface of limit equilibrium. According to the reviewers' comments, he is very close to the truth here, but he has reversed the proactive and reactive roles between groundwater flow and heat convection.

Examination of these profiles does confirm an increase of thermal gradient with depth, but it is gradual rather than "sharp." The cooler excursion at a depth of about 1000 m in the USW G-1 log, which was obtained in April, 1981, is much smaller than the corresponding excursion on the log of September, 1980. Sass et al. (1988) state that the hole had not completely recovered from the drilling disturbance, indicating that the loss of drilling fluid at this depth was large and, hence, the fracture permeability is also large. Discounting this excursion, the profile is linear and apparently conductive. This is consistent with the apparent thermal equilibration below 1000 m, which suggests little loss of drilling fluids and low permeability. Sass and Lachenbruch (1982) had core samples on which to measure thermal conductivity from USW G-1, calculating a heat flow of 52 mWm^{-2}, or 1.24 HFU.

In the absence of core samples from USW H-1, Sass and Lachenbruch (1982) did not report heat flow there. However, Sass et al. (1988) report two estimates, one by estimating the conductivity from the means established for the equivalent stratigraphic formations elsewhere in the vicinity, and the other from an empirical correlation of conductivity with compressional wave sonic velocity. Respectively, the reported heat flows were 54 mWm^{-2} (1.3 HFU) and 46 mWm^{-2} (1.1 HFU).

There is a possibility, however, that the heat-flow estimates for USW H-1 are too large, because this hole, as discussed previously, displays a substantial increase of hydraulic head with depth, providing the potential for upward flow both in the formation and, more likely, in the borehole. Note that the lower 150 m of the temperature profile displays the upward convexity that is diagnostic of upward flow in the borehole and which rotates the thermal profile to give a larger gradient than that in the rock mass. The effect appears to be very minor, not more than a few percent.

It is concluded from this analysis that the author is correct that fracture permeability decreases with depth at these locations, but not that limit equilibrium is the cause. If it were the cause, the change of gradient would be more distinct, and the heat flow calculated from data obtained below the surface of limit equilibrium would be ~2 HFU, the Basin and Range average, rather than ~1.2 HFU. It appears that there is underflow of water, at some depth greater than 1800 m, that is cool relative to the "normal" geotemperature at that depth. The lower carbonate aquifer is probably present beneath the general location of USW G-1 and USW H-1, which has been a point of speculation for some in the absence of drilling data. As was discussed previously, this aquifer has been penetrated about 5 km to the southeast at a depth of about 1200 m in drill hole UE25p-1, which was sited on a gravitational high. If it is present beneath central Yucca Mountain, it is deep and in a favorable position to act as a heat sink.

5. SUMMARY

These analyses indicate a very close and complementary relationship between hydraulic characteristics and temperature as measured in a borehole that has connected permeable zones which, in nature, are very poorly connected. The data contrast strongly with the author's idealized profiles used to demonstrate underpressure and overpressure. The typical set of borehole-test data from Pahute Mesa includes zones where both downward and upward flow converge. Intermixed layers of overpressure and underpressure seem fundamentally contrary to an origin from deep processes. Similarly, the data from Yucca Flat, the Calico Hills, and Yucca Mountain are inconsistent with the author's model when the data are examined as cohesive, complementary sets within each area rather than in piecemeal fashion; the author commonly draws inconsistent conclusions regarding the same area but from different, limited sets of data. In contrast, reviewers found the data to be consistent with a conceptual model that emphasizes hydrogeologic control of groundwater flow and resulting hydroconvective transfer of heat, both within the individual areas and for the region as a whole.

G. EFFECTS OF MECHANICAL AND HYDRAULIC STRESSES

Section 4.7 of the manuscript addresses field evidence of reactive hydrologic response to short-term changes in the state of stress, whether they are directly applied or they are, in turn, reactions to imposed hydraulic stresses. Reference is also made, in Sections 4.1 and 5.1 of the manuscript, to the potential significance of stress-related changes of hydraulic potential at Yucca Mountain in supporting the author's thesis that the base of "limit equilibrium" is declining.

1. UNDERGROUND NUCLEAR EXPLOSIONS

The manuscript introduces on Pages 3-17, 3-19, and 4-23 through 4-25 the proposal that underground nuclear explosions (UNE's) provide analogs for the hydrologic effects of tectonic events, claiming that tens of meters of change in the position of the water table have occurred (Page 3-17) and that "the involvement of [the] deforming fractured medium [is demonstrated by]: a) large scale oscillations of the water table occurring long after passage of the detonation induced shock waves; and b) sustained, but localized, water table changes resulting in formation of hydraulic mounds or hydraulic sinks" (p. 3-19). Reviewers expressed doubts as to the relevance and magnitudes of UNE effects, noting that UNE's are much shallower and spatially more concentrated sources of energy release than are earthquake focal zones. However, strain events or aftershocks induced by a UNE may be reasonable analogies if they are sufficiently distant from the direct disturbance.

The analog is repeated on Page 4-23 with respect to dynamic (seismic-phase) response to both earthquakes and explosions. However, the author fails to note that his sample calculation of the transient pressure response to a magnitude 7.5+ earthquake at 30 km would result from an energy release an order of magnitude greater than that of a 1-megaton UNE, possibly leaving some readers with the impression that large areas of the Nevada Test Site and Yucca Mountain have repeatedly experienced fluid overpressures of tens of bars.

The effects of two UNE's on the hydrologic system were selected for discussion in the manuscript. The first, the Bilby event, was detonated beneath the water table in Yucca Flat, a topographically closed basin with thick alluvium and tuffs overlying the Paleozoic lower carbonate aquifer. The second UNE was Handley, detonated beneath the water table in western Pahute Mesa, a volcanic upland underlain by tuffs and rhyolite lavas to depths of at least a few thousands of meters (>4,171 m at hole UE-20f). As discussed previously in this review, hydraulic head decreases downward to the carbonate aquifer beneath Yucca Flat, indicating recharge to the aquifer. Beneath the western part of Pahute Mesa, the hydraulic gradient in the deeper part of the saturated zone is generally lateral but with an upward component toward preferential flowpaths in the fractured, more permeable rocks in the upper part of the saturated section.

The manuscript's descriptions of the dynamic-phase hydraulic responses are generally in agreement with those in the cited references, though they fail to distinguish clearly between actual changes of the water-table altitude, the pressure response in a well penetrating the saturated zone but confined with an inflatable packer, and water-level changes in an open well acting as a piezometer. This leads to the erroneous implication that dynamic-phase responses to large UNE's, which release seismic energy equivalent to earthquakes of magnitude 5.5 to 6.5, provide the scale of water-table changes that might attend such earthquake events. Large increases of pressure in water that is confined in rock can be relieved by relatively small changes of storage as water seeps away from zones of high pressure.

In discussing the hydrologic effects of UNE's, it is useful to define four fields or scales of consideration:

(1) The very-near field, which initially consists only of the cavity formed by the intense heat and pressure at the instant of the explosion, but later includes also the rubble chimney that forms upward by collapse of overlying materials into the cavity.

(2) The near field, in which the rock mass is pervasively compacted and which may be injected by gases and rock melt.

(3) The intermediate field, in which seismic stresses may locally crush points of fracture contact and in which secondary movement on existing faults (aftershocks) may occur.

(4) The far field, in which only the dynamic effects of the passing seismic waves are usually significant, although small changes of porosity locally and infrequently cause minor (centimeters to a few meters) changes of hydraulic head after natural earthquakes.

There is a reasonable understanding of the hydrologic effects within these fields. Predictions of peak dynamic-phase responses, such as is shown on Plate 4.7.2-6 from Dudley et al. (1971), relate the confined fluid-pressure response in the intermediate and far fields empirically to device yield and distance, with accuracy generally within a factor of two. Sustained effects are understood only conceptually, although there are some observations that give tentative guidance as to the nature and scale of effects. Borg et al. (1976) provide a comprehensive overview of UNE effects, particularly as they relate to hydrology and radionuclide migration. Buddemeier and Isherwood (1985) compiled a similar overview, though updated by a decade, for the studies of these phenomena at the Nevada Test Site. The most detailed analysis of the hydrology and radiohydrology in the very-near and near fields after a UNE is provided by Claassen (1978).

The explosion cavity is voided of water within milliseconds after a nuclear detonation. In minutes to days after the explosion, the roof of the cavity collapses, and upward stoping forms a rubble chimney, in most cases extending to the surface to form a subsidence crater. Most of the initial cavity volume is distributed between blocks of rock in the rubble chimney as bulking porosity. Those parts of the cavity and rubble chimney that extend beneath the water table are suddenly transformed into an unsaturated mass intruded into the saturated rock, forming a true hydraulic sink in the water table. During post-shot drilling to recover samples of the melt for device diagnostics, drilling-fluid circulation is usually lost when the rubble chimney is entered. The gradual recovery of the water level has been studied at several sites since the original work of Garber (1971) at the Bilby re-entry hole, U3cnPS#2 (Borg et al., 1976; Claassen, 1978; Buddemeier and Isherwood, 1985).

In the near field, the pervasive compaction of the rock mass causes large and immediate increases of fluid pressure for distances that are not well defined and that are probably heavily dependent on local geology. In some areas of Yucca Flat, holes that are drilled within several cavity radii of expended sites frequently encounter the water table at expected depths but, upon deepening, penetrate overpressured zones that cause a piezometric rise of fluid in the hole. The rates of water-level rise are low, indicating that the overpressured zones are not highly permeable. Rises of more than 200 m above the water table have been observed in on-going monitoring at Yucca Flat. Unfortunately, there are no test holes closely adjacent to a rubble chimney that might provide information on the potentiometric history at the inner near-field range. Presumably, drawdown occurs in the more permeable intervals as water flows toward the evacuated rubble chimney.

Where underground testing beneath or close to the water table has been intense, as in Yucca Flat, "water table changes resulting in hydraulic mounds or hydraulic sinks" do, in fact, occur. The mounding that occurs in this instance is, however, thought to be only potentiometric in nature. Hence a tectonically deforming medium is not indicated. The generally understood phenomenology of UNE's has been consistent with observations in the tectonic environments not only of the Basin and Range, but also in those of the central Rocky Mountains (Plowshare tests) and the Aleutian Islands (high-yield weapons tests).

In the manuscript, the decline of water level in the very-near field at Bilby is attributed to opening of fractures downward to or beneath the carbonate aquifer by fluid pressure driven by the Bilby explosion. By some unexplained mechanism the fractures are proposed to have remained in a dilated state while the water drained to a hydraulic potential almost 100 m lower than that in the carbonate aquifer, and then to have closed to restore isolation of the tuffs from the "underpressure," allowing the water level to begin recovering. The same process is offered as one explanation for sustained higher fluid pressures at about 5 km from the Handley event, in that case the fractures providing communication with the "overpressure" at depth. However, water levels in the near field in western Pahute Mesa, where there is an increase of head with depth (Blankennagel and Weir, 1973), have been shown in post-shot re-entry drilling to be depressed to near the base of the cavity, just as they are in Yucca Flat (Buddemeier and Isherwood, 1985). The mechanistic speculations in the manuscript fail to explain observed phenomena consistently, whereas the observations are consistent with the conceptual understanding developed in the UNE programs, both weapons-related and Plowshare. Further, the postulated but unexplained delay in elastic closure of fractures at Bilby until the water level had declined, coincidentally, just to the base of the cavity strongly suggests that the speculation is lacking in merit. Finally, sustained pumping from well U3cn-PS#5, completed in the carbonate aquifer directly beneath the Bilby cavity, has demonstrated that no radioactivity was injected into the aquifer (Buddemeier et al., 1985), a finding that would be highly unlikely if water had first been forcefully injected from the cavity and later drained through it into or through the aquifer.

Discounting the temporary establishment of vertical communication with the "overpressure" at depth, we next turn to the manuscript's alternative explanation of hydraulic responses observed after the Handley event on Pahute Mesa (Pages 4-26 to 4-29). First, the manuscript fails to specify the nature of the instrumentation and the consequent limitations of the data, most of which were described by Dudley et al. (1971). The fluid columns were confined with inflatable packers in boreholes UE-20f and UE-18r in order to record the actual transient pressures during the passage of the seismic waves. Strain-gage transducers (absolute) were suspended beneath the packers. The water columns in boreholes UE-20p and PM-2 were not confined and were expected to respond efficiently only to sustained pressure changes that would allow sufficient time for water to move into or out of the boreholes. Instability of power supplies, transducer ranges (selected to survive maximum predicted effects), system hysteresis, and the lack of compensation for barometric effects suggest that no significance can confidently be assigned changes of less than a few meters in UE-20f, about 1 m in UE-18r, and about 0.5 m in UE-20p and PM-2, particularly with respect to long-term behavior. Consequently, the apparent residual increase of head in UE-20f that is noted in the manuscript (Page 4-27) may or may not be real; the same caveat must be applied to the apparent residuals (Plate 4.7.2-8) at UE-18r and PM-2, as well as to the apparent lack of residual effects at UE-20p. The gradual recovery at PM-2, however, suggests that the local pressure excursion was of at least weeks but probably not more than a few months in duration. Testing of this hole revealed that it penetrated tuffs having very low permeability (Blankennagel and Weir, 1973).

As discussed previously, reviewers questioned the applicability of UNE response data to predicting response to natural earthquakes because of the relatively shallow and spatially concentrated source of energy afforded by a UNE. Phenomena occurring in the very-near and near fields probably are unique to UNE's. However, the variety of effects observed at about 5 km (UE-20f, UE-20p, and PM-2) from Handley suggest that this distance is within the intermediate field, where the fluid-pressure responses after the dynamic phase are only indirectly attributable to the explosion. It seems reasonable to attribute the effects to induced tectonic events occurring quite close to the observation sites, as was proposed by Dudley et al. (1971). However, the times of the pressure excursions did not correlate well with instrumentally determined aftershocks, suggesting that they were either aseismic or very small in magnitude. On Pages 4-28 and 4-29, the manuscript considers explosion-induced alteration of stresses on fractures, although it leads to a rather intuitive discussion of an elastic struggle between fluid pressure and fracture aperture, in which fracture closure increases fluid pressure which then forces the fractures back open in a repeating cycle; that is, the role of the fluid alternates from reactive to proactive with periodicities of days to weeks. This is inconsistent with the theory and observed periodicities of inertial, oscillatory response of aquifers to mechanical disturbance (Cooper et. al., 1965; Bredehoeft et. al., 1965; Dudley and Larson, 1976; Dudley et al., 1971). Such oscillations do indicate elastic response of the aquifer system, but periods range from seconds to tens of seconds.

Instead, we propose that the fluid-pressure excursions observed in the days to weeks following Handley were strictly reactive to localized rock-mass strains that were adjusting to disruptions from the intense seismic waves, the sustained radial stress (in part relieved by chimney collapse), and aftershocks. The magnitudes of the pressure excursions are of interest. The greatest of the post-seismic excursions were less than 30 m of water; in stating a rise of 50 m in UE-20p, the author failed to recognize the arbitrary base of the water-level axis on Plate 4.7.2-10, which included atmospheric pressure and pressure due to submergence of the transducer beneath the undisturbed water level. The excursions were of pressure only, not of water-table position, and involved very small quantities of actual water transfer into and out of the boreholes. The ratio of unconfined (water-table) storage coefficients, about 10^{-2} to 10^{-3}, to that for confined conditions, 10^{-5} to 10^{-6}, suggests that these excursions would be attenuated by two to four orders of magnitude if the pressure were released upward and without opportunity for lateral dissipation. Thus, the equivalent water-table rise would be measured in terms of a few to a few tens of centimeters. The rates of decline of the excursions attest to the opportunity for lateral dissipation of pressure anomalies in the affected rocks.

The observed potentiometric excursions are believed to have been in reaction to induced tectonic events of rather small scale, so we cannot assume with confidence that the Handley effects are similar to those expected from natural events of larger scale. Nonetheless, the data show that, at ranges experiencing on the order of 100 m of reactive potentiometric response to the seismic phase, the post-seismic effects were much smaller and persisted only for a matter of weeks. There is no evidence of massive, persistent changes of rock-mass strain that detectably altered the hydraulic properties of the medium.

2. HYDRAULICALLY INDUCED EFFECTS

It is proposed in the manuscript that coupling of hydraulic and mechanical processes is indicated by the results of tests in boreholes that measure responses induced by the application of fluid pressure. The consideration of coupled processes, although not a new concept, certainly promises a more complete rendering of the physical system than considerations involving only one of the processes. Because it dramatically raises the complexity and mathematical intractability of modeling the system, the incorporation of coupled processes in physical-based models is rarely undertaken.

The author attempts to demonstrate that the field evidence from in situ stress (hydrofrac) tests and hydraulic slug tests in boreholes supports the need to consider the coupled processes in the context of groundwater flow in a tectonically deforming medium. His analysis purports to show that the fluid-mechanical system is delicately balanced at a "limit equilibrium" such that relatively small (tens of meters) changes in fluid pressure can cause fracture deformation with concomitant changes of specific storage and hydraulic conductivity of the medium.

Both hydrofrac and slug tests are conducted by isolating intervals of the borehole between inflatable packers and injecting relatively small volumes of water into the isolated zone. A procedural objective in the hydrofrac test is to minimize the injected volume so as not to perturb unduly the in situ hydrostatic pressure in the interstices of the rocks. In the slug tests, the small volume is a limitation of the procedure that is not necessarily desirable, as the hydraulic properties derived from the results are usually applicable only to a relatively small volume around the borehole (Dougherty and Babu, 1984).

a. Hydrofrac Tests

Hydrofrac tests are performed to measure the magnitude of the least principal axis of the stress tensor. Fluid is injected, first, to raise the pressure in the borehole to a level that induces a new tensile fracture in the formation and, then, to determine the pressure required to maintain incipient dilation of the fracture. The orientation of the induced fracture, which is determined by supplemental means, and the fluid pressure at incipient fracture dilation allow quantitative estimates of the direction and magnitude of the least principal stress.

A tectonic regime of strike-slip faulting is indicated when the greatest principal stress is subhorizontal, whereas normal or dip-slip faulting is indicated when the lithostat is the greatest. However, it is questionable whether the tests conducted at Yucca Mountain are deep enough to reveal the "regional" stress tensor, because of near-surface and topographic effects (Swolfs et al., 1988; Stock and Healy, 1988). For analysis of hydrofrac data in terms of shear failure, both the least and the greatest principal stresses must be known. The greatest principal stress is assumed to be vertical and estimated to be equal to the lithostatic lead. The reader should be aware, however, that the greater horizontal principal stress, assumed here to be the intermediate, closely approaches the lithostatic stress and may, in places, actually be the greatest principal stress.

The description given in the manuscript of the results and interpretations of the hydrofrac tests reported by Stock et al. (1985; 1986) are in general agreement with those papers. These papers, respectively, indicate that: "The measured stresses are near the limit of those required to cause slip on favorably oriented pre-existing faults...", and "...the minimum principal stress values measured from hydrofrac tests are very close to the values at which slip would occur on favorably oriented faults." The contention made by the author that the system is at the "limit equilibrium" may be an overstatement, but the magnitudes of the stresses are nonetheless of interest for their tectonic implications, for engineering purposes, and for interpreting slug-test data.

Results from the hydrofrac tests in USW G-1 (Stock et al., 1985), reproduced as Plate 4.5-5 of the manuscript, indicate that at a depth of 792 m the magnitude of the least principal stress was 7.2 MPa. The hydrostatic fluid pressure was 2.2 MPa at this depth, and the normal effective stress for a planar fracture oriented normal to the axis of the least principal stress would be about 5 MPa, which is roughly equivalent to the static pressure exerted by a 500 m column of water. Theoretically, then, exceeding the least principal effective stress and thus opening a favorably oriented, pre-existing fracture in USW G-1 would require the application of about 500 m of head greater than that represented by hydrostatic pressure ("static water level") in the tested zone, which is generally close to the head represented by the water-table altitude.

The coefficient of friction for tuffs at Yucca Mountain is usually taken to be between 0.6 and 1.0 based on laboratory tests (Morrow and Byerlee, 1984). The difference between the greatest principal effective stress and the least principal effective stress indicates that fluid-pressure changes from 90 to 290 m, computed for values of the coefficient of friction of 0.6 and 0.9, respectively, could exceed the resistance to shear failure or slip on favorably oriented fractures. Extending this analysis from the scale of a small volume around the tested borehole interval to the scale of a significant portion of an actual fault surface gives rise to the conclusions, quoted above, of Stock et al. (1985, 1986) and to the author's assignment of "limit equilibrium" conditions to Yucca Mountain. (For reference, most of the slug tests referred to in the manuscript were conducted using initial injection heads greater than 290 m; typically they were about 500 m, and several exceeded 600 m.)

b. Slug Tests

Slug tests are designed to measure the fluid-flow properties of the rock by the instantaneous application of an incremental fluid pressure (positive or negative) and measuring the decay of the increment over time as the slug drains into, or is released from, the tested zone. For most slug tests, including all of those that have been conducted at Yucca Mountain, the initial increment is positive. Cooper et al. (1967) describe the test procedure, the assumptions, and the analysis of slug tests. They describe the slug test as useful only for geologic materials of rather low permeability.

An assumption inherent in the analysis of slug tests is that the fluid-flow properties of the rocks are not functions of fluid pressure, and therefore the tests should be designed to mitigate the influence of formation mechanical effects. However, if the initial head of the slug is large enough to cause formation fluid pressures to meet or exceed a level that causes deformation of pre-existing fractures or causes fracture propagation, then the pressure transients may reflect coupling or interaction of the fluid and mechanical systems. We agree with the author to the extent that many of the slug tests conducted at Yucca Mountain demonstrate coupling of the mechanical and hydraulic properties of the rock mass with injection fluid pressures, as was discussed by Thordarson et al. (1985).

The manuscript interprets the slug-test results in the context of effective stress, and of the Griffith-Navier-Coulomb and Navier-Coulomb failure criteria. The author makes several fundamental errors in the analysis of stress conditions attendant to the slug test. The first is the role of fluid pressure, p, in the relation of effective stress, σ', to total stress, σ; (e.g., Page 4-30),

$$\sigma_1' - \sigma_3' = (\sigma_1 - \sigma_3) - p ,$$

where σ_1 and σ_3 represent the greatest and least stresses, respectively. The correct relations are:

$$\sigma_1' = \sigma_1 - p \text{ and } \sigma_3' = \sigma_3 - p , \text{ or}$$

$$\sigma_1' - \sigma_3' = \sigma_1 - \sigma_3 .$$

The effective stress difference in a saturated rock mass is the same as the total stress difference because the fluid pressure acts equally in all directions. However, the magnitudes of the effective normal stresses of any orientation, including the principal stresses, are less than those of the total normal stresses by the amount of the fluid pressure (Terzaghi and Peck, 1948). The effect of a pervasive increase in fluid pressure throughout a uniformly stressed body of rock is to shift the Mohr circle for total stress to the left, that is, toward the Navier-Coulomb failure envelope or, if tensile strength is sufficient and the value of $\sigma_1' - \sigma_3'$ is small enough, toward the Griffith tensile-failure point.

The Griffith-Navier-Coulomb failure criteria and Mohr-circle analysis are not easily adaptable to localized point injection of a small volume of water into fractures in an extensive rock body. Unless sustained injection affects a large volume of the rock, any tendency for shear failure is immobilized by the lateral restraint of the rock body. Instead, as the fluid overpressure in the fracture around the injection point approaches the original normal stress across the fracture, the shear stresses are transferred outward along the fracture walls and into the wallrock. Where the change in fluid pressure reaches or exceeds the normal stress across the fracture, no shear stress is supported by that part of the injected fracture. The stress tensor rotates such that the least principal stress (σ_3) acts normal to the fracture, and the greatest and intermediate axes (σ_1 and σ_2) are parallel to the fracture plane. Microfractures may form where shear-stress concentrations are large enough, but they probably are not accompanied by shear motion or dilation in the small, constrained volume of rock affected by a slug test. This suggests that the relationship of fluid pressure to slug velocity, reflecting both shear and tensile failure, as expressed on Plate 4.7.4-3 in the manuscript, are conceptually unsuitable for slug-test analysis.

The discussions of the local perturbations in the in situ strain energy field (Pages 4-24, 4-25; Plates 4.7.1-2 through 4.7.1-4) are perhaps justifiably simplified for conceptual reasons. However, the limitations and assumptions inherent in the simplified analyses are not stated in the manuscript. One important limitation arises from the apparent assumption of a uniform fracture-aperture distribution. The assumption follows from the initial distribution of the shear and normal stresses (Plate 4.7.1-2). As such, the effects of asperities and the nonuniform distribution of aperture, characteristic of natural fractures, are neglected. Hence, application of the author's conceptual analysis to the tests at Yucca Mountain is limited by the assumption that the fluid pressure exerted in the fracture is pervasive (i.e., distributed throughout the fracture surface). Because fractures are not smooth planar features, these theoretical results may differ from the field case. Fracture-deformation measurements (Gale, 1975) have shown that the magnitude of the change in fracture aperture is related in part to the fluid-pressure distribution in the fracture surface and thus to the degree of aperture uniformity. Many studies have demonstrated the significant effect of fracture roughness on the dilatory and shear strength of natural fractures (Jaeger, 1971; Ohnishi and Goodman, 1974; Rengers, 1970).

The effects of fracture roughness on the measured hydraulic response to hydraulic stress tests of fractures intersecting the borehole may be manifested in two extreme cases. First, if the fracture aperture is large and thus the permeability, the imposed fluid pressure in the borehole may be transmitted with relatively small head losses through the plane of the fracture to the extent of flow-limiting constrictions. This could have the effect of distributing fluid-pressure changes over considerable distances along the fracture, although the effect is ultimately limited by the volume of the injected slug if additional fracture separation is induced. Secondly and conversely, if the constriction occurs near the borehole, propagation of the fluid pressures is limited. The consequences of the two extremes have interdependent spatial and temporal ramifications. Spatially, the initial hydraulic stress may be distributed over a larger or smaller area of the fracture plane. The transience of the propagating pressure pulse would be related, in part, to the aperture size and the effective hydraulic diffusivity, but would be bounded by the flow-limiting constriction. Witherspoon and Gale (1977) note that "the interaction of the mechanical and geomechanical properties of fractures with fluid pressure distributions should be thoroughly investigated when one is considering ... the state of stress around a borehole."

The concept of effective stress in the Griffith and Coulomb criteria for failure assumes that the permeability and connectivity of the pores or fracture apertures are sufficient to transmit pressures readily and evenly through the medium. This is an important and limiting assumption when considering failure envelopes for in situ fractures characterized by nonuniform aperture distributions. The effect of changing shear stresses over reasonable ranges of effective normal stress, flow rates, and permeability through rough fractures is not clear from the published literature. Witherspoon and Gale (1977) noted: "this is an area of research that needs much more work, especially when one considers dilatancy in shear modes."

At very high rates of slug drainage (which, for the slug-test method, corresponds to test zones of rather high transmissivity), the nature of the recovery may be additionally complicated by the effects of turbulence, either through the injection portals of the packer string or in the fractures themselves. The portals also have the potential for functioning as flow-limiting constrictions (i.e., as "chokes" at critical flow). A few tests exhibited essentially complete (>95 percent) recovery within 2 to 3 minutes and are not quantitatively interpretable by the slug-test technique. They show only that the tested zones are "highly permeable". A transmissivity of >2 m^2/day is "highly permeable" in this context. Such tests do suggest, however, that the injection portals have not significantly impeded flow for tests that recover at slower rates, providing apparently interpretable results.

Whether the characteristic hump or step in the recovery curves measured in many slug tests at Yucca Mountain is the result of changing fracture aperture due to dilatancy resulting from shear, or from fracture separation due to decreased normal effective stress, the data would indicate that the effective hydraulic aperture does change during some slug tests, as recognized by Thordarson et al. (1985). However, particularly early in a high-stress test, the hydraulic response may be clouded by several other possible mechanisms that may be affecting the pressure transients, such as borehole storage effects or the effects of fluid turbulence. In addition, inertial oscillatory response to the sudden application of high head apparently complicates the early part (first 1 to 2 minutes) of many of the curves, overwhelming borehole storage effects and, with little doubt, involving the mechanical participation of the rocks (Cooper et al., 1965). Therefore, although the reviewers disagree with many details of the author's interpretation, they do agree that coupling of the hydraulic and mechanical systems is demonstrated by the stepped recovery curves.

i. Constitutive Relationship

The manuscript proposes that the curves on Plate 4.7.4-3, which relate the log of slug velocity to fluid pressure (arithmetic scale) in the injection zone, provide patterns that allow recognition of fluid pressures at which the Navier-Coulomb criterion for shear failure and the Griffith criterion for fracture separation are met. Conceptually, they are represented to show the following stress conditions:

(1) The type A curve corresponds to the assumption, inherent in the analytical solution (Cooper et al., 1967), that the hydraulic properties are independent of pressure, i.e., the entire recovery occurs at pressures below those required to produce shear failure or fracture separation.

(2) The type B curve is proposed to represent a test in which the pressure initially exceeds and then declines through the value for shear failure, forming a step on the recovery curve.

(3) The type C is proposed for tests in which the pressure initially exceeds and then declines through the values required for both fracture separation (step at higher pressure) and shear failure (step at lower pressure).

(4) The type D curve applies when all but the latest stages of the recovery occur at pressures which exceed that required for fracture separation, (i.e., fracture aperture is initially large but decreases with declining fluid pressure throughout the test); therefore, it corresponds with very small values of effective stress across the fracture, and the recovery is very rapid.

The manuscript describes the recovery rate, rather than curve shape, as the more useful feature for distinguishing between type A (very slow) and type D (very fast).

According to the author's concept, then, high apparent permeability occurs only when in situ stress is very low, and the fracture separation induced by the fluid pressure controls that permeability. Alternatively, according to his conceptual model, low permeability is inherent in rocks that are unfractured or whose fractures are closed tightly by the in situ stress.

The curves are apparently conceptual only, rather than having been calculated from the mathematical formulation of slug-test theory by Cooper et al. (1967), as they are inconsistent with the same relation calculated from this theory. The theoretical curve should be comparable to those for the author's type A and to late times (small pressures) for types B, C, and D. The main differences are that the velocity of the slug on the theoretical curve declines throughout the recovery period, in contrast to the type A curve, or that the curve continues to steepen (to the left) as the pressure declines in the late stages of the test, in contrast to all curves but particularly to the final stage of the type D curve. Consequently, it seems that these conceptual curves are speculative and are supported neither by theory nor by hydrogeologic principles. Furthermore, they are not directly comparable to the recovery curves of Plates 4.7.4-5 through 4.7.4-12f, as these plot water level (pressure) on an arithmetic ordinate against time on a logarithmic abscissa.

ii. **Tests In USW H-3**

For purposes of testing the concept against actual field results, data from the slug tests in USW H-3 (Thordarson et al., 1985) are reproduced here in Figure II.G-1. The data are comparable to those presented in the constitutive relationship, as injection rate is proportional to slug velocity, but the axes are oriented differently and both are arithmetic. The manuscript classified each of these tests in one of three (type B, C, or D) of the four types shown on Plate 4.7.4-3. These designations are shown on Figure II.G-1.

Significantly, there were no curves classified by the author as type A in the test results from USW H-3; all were considered to show coupling of fracture dilation to fluid pressure. Note on the legend of Figure II.G-1 that the most "relaxed" state of stress is assigned to the shallowest zone tested, the least "relaxed" to the zone immediately below, and the intermediate state to the four deeper zones. However, proximity to failure is a function not only of the state of stress, but also of the mechanical properties of the rock. There is no apparent lithologic control: the upper three zones tested are in the Tram Member of the Crater Flat Tuff, described in Thordarson et al. (1985) as "mostly partially welded, devitrified"; the deepest test was in "partially welded, partially zeolitic(?) and argillic(?)" Lithic Ridge Tuff; the next-to-deepest zone spanned the lower Tram and upper Lithic Ridge and an intervening bedded tuff of 9 m thickness; the large-interval test (972 to 1,219 m) spanned the two deepest tested zones as well as the otherwise untested interval from 972 to 1063 m (i.e., it included approximately equal sections of Tram and Lithic Ridge and the bedded tuff). Analysis of geophysical logs (Thordarson et al., 1985) showed the Lithic Ridge Tuff (type C test) to be more porous than the average, the second-shallowest zone (851 to 917 m; type B test) to have the least percentage of porous rock, and the rocks in the intervals 792 to 850 m, 911 to 972 m, and 1,063 to 1,124 m (types D, C, and C, respectively) to have intermediate percentages of porous rock. The test (type C) spanning 972 to 1,219 m ranks second-highest in percent of porous rock. There is no apparent correlation of type designation to either stratigraphy or to porosity, making highly suspect the interpretation that adjacent zones contrast strongly in their susceptibility to failure.

Test interval 1,126 to 1,219 m in USW H-3 (Figure II.G-1) is classified as type C in the manuscript. The rate of decline of injection rate decreases with the decline of pressure from 7 to about 5.5 MPa. This requires, according to the constitutive relationship, that the Griffith criterion be about 6 MPa. Another possible explanation is that the flattening of the curve in the range of 7 to 5.5 MPa represents the transition from turbulent to laminar flow. However, all of the curves are erratic in the first minute of recovery (Thordarson et al., 1985, Figure 10), occurring at pressures generally above 5 MPa, and they probably are exhibiting inertial effects and oscillatory reaction to the sudden applications of high pressures. Hydrofracing at the highest pressures also cannot be ruled out. Below about 3 MPa the measured pressure-transient behavior of the tests approaches that of the Cooper et al. (1967) type curves, and indicates that the Griffith

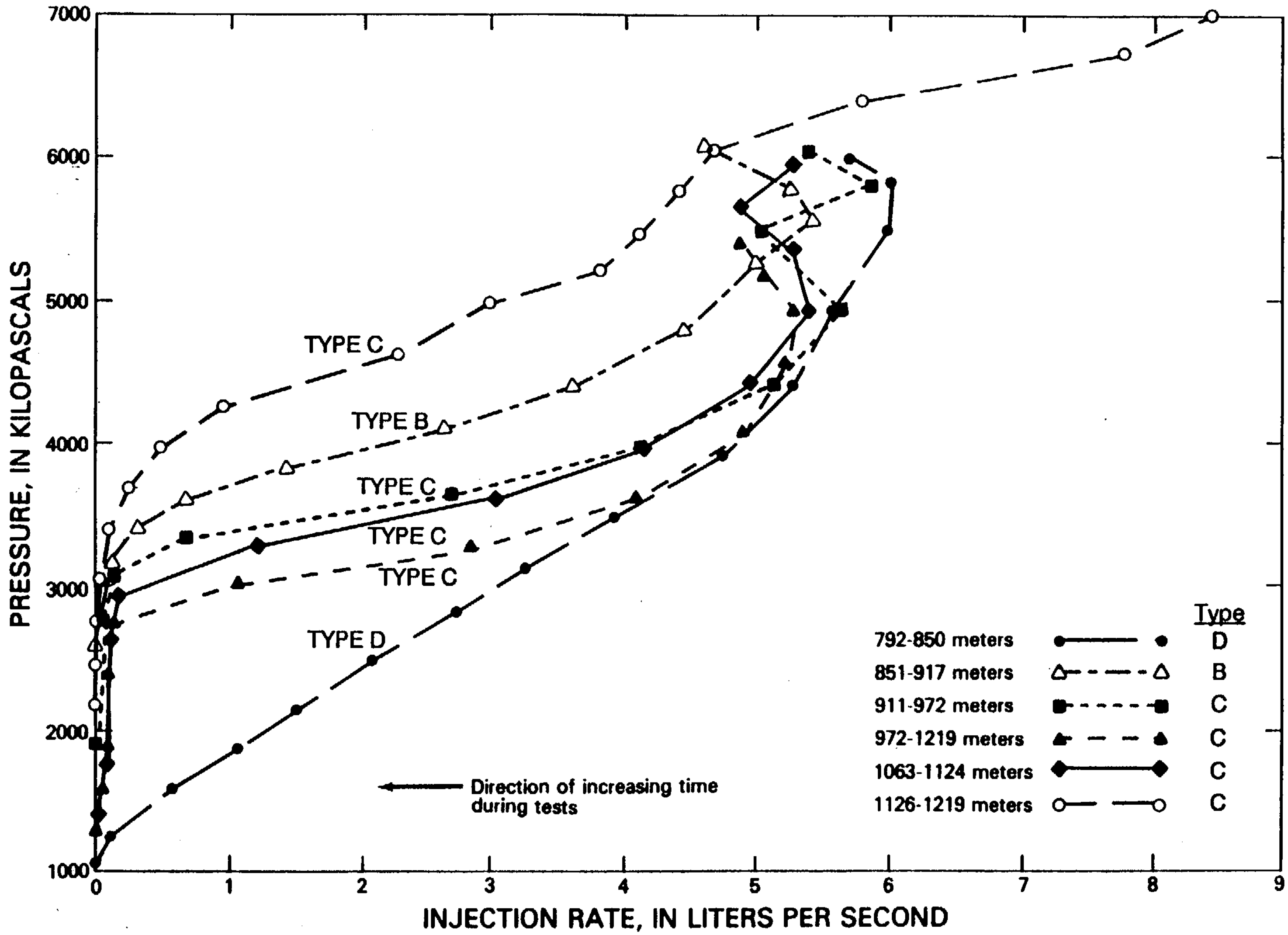

Figure II.G-1. Relation of pressure and injection rate during injection tests in USW H-3. Curve-type designation is from the draft manuscript under review. Adapted from Thordarson et al., 1985.

criterion is more likely about 3 MPa. In fact, the curves on Figure II.G-1, excluding that for 792 to 850 m, all exhibit a convergence within the range of about 2.8-3.5 MPa at an injection rate of about 0.1 L/s. Below the convergence pressure, the curves deflect sharply, and the decline of head continues at a very small rate. This strongly indicates the closure of fractures at this approximate fluid pressure, as stated by Thordarson et al. (1985). Between about 5 MPa and about 3 MPa, the type B and type C curves are similar in shape, which for previously fractured rock suggests a simple dilational relation between fluid pressure and fracture permeability.

The curve on Figure II.G-1 for the interval 792 to 850 m, designated type D in the manuscript, is obviously different. If the designation is correct, then 1.3 MPa is larger than the closure stress on a pre-existing fracture oriented perpendicular to the axis of the least principal stress, indicating a very small normal stress. On the recovery curves in the more usual format, this test (Plate 4.7.4-6, top) did not exhibit the characteristic stepped recovery evident in the other curves obtained from testing in USW H-3 (Plates 4.7.4-6, bottom; 4.7.4-6a and 4.7.4-6b). Instead, the recovery provided a fairly good match to theoretical type curves. This suggests either that the interval has dominantly interstitial permeability or that it is pervasively fractured and behaves almost as an equivalent porous medium of moderate permeability. The curve for this test on Figure II.G-1 demonstrates a linear relationship of injection rate to pressure in the time period 1.5 to 10 minutes, when the recovery was 90 percent complete. Thordarson et al. (1985) used this to interpret that the hydraulic properties were independent of injection pressure.

The transmissivity calculated for the slug-injection test in this interval (792 to 850 m) was 1.2 m^2/day (Thordarson et al., 1985), indicating rocks of rather low permeability. The borehole flow survey in USW-H3 indicated that this interval accepted 63 percent of the total during constant-rate injection of 2.7 L/s into the entire borehole, 792 to 1,219 m. At a proportioned injection rate of 2 L/s, the most permeable zone would have controlled the injection pressure at about 2.5 MPa, which should not have dilated the fractures in the zones displaying type B or C responses. Recovery of the entire borehole after being drawn down by swabbing indicated a transmissivity of 1.1 m^2/day, of which 0.7 m^2/day was attributed to the "Type D" interval, 792 to 850 m, by Thordarson et al. (1985) in their analysis of the composite data set. The difference between 0.7 and 1.2 m^2/day is probably not significant, particularly given the quality of the match of the slug-test data to the type curve (Figure 13 of Thordarson et al., 1985 and Plate 4.7.4-6 in the manuscript), which was placed to provide the highest transmissivity that could be derived from the data. (A better estimate might have been obtained by matching the curves at 50 percent recovery, which provides a transmissivity of 0.8 m^2/day). However, the data might be interpreted to suggest a slight decrease of productivity under drawdown as compared with injection stresses. Nonetheless, the "type D" zone, characterized in the manuscript as the zone most sensitive to stress in USW H-3, maintained under the drawdown condition between half and all of its transmissivity for injection stresses. All or most of the productivity of this zone, the most permeable in USW H-3, must be attributed to the durable characteristics of the rock, not to fracture-aperture response to stress.

As many, if not all, of the " type D" responses (e.g., USW H-5, USW H-6, and UE-25p#1) are associated with "most permeable zones" having invariant properties, the diffusion of the injection pressures in these zones would be more pervasive spatially, and the changes in effective stress would be distributed differently than in those less permeable zones dominated by a single fracture or few fractures. Perhaps the spatial distribution of the change in effective stress can explain the differences in shapes of the curves (Figure II.G-1) below 5 MPa.

Returning to hydrofrac tests to determine if there is consistency among the data, Stock et al. (1985) report in situ stress tests in USW G-3, which is 1.1 km south of USW H-3. The holes are at similar surface altitudes and penetrate similar stratigraphic sections. One test, at 1,074 m, was within the depth of interest with respect to the slug tests in USW H-3. Subtracting the hydrostatic pressure in USW H-3 (3.3 MPa) from the least principal total stress (6.8 ± 0.2 MPa) we can estimate a least principal effective stress of 3.5 MPa near the center of the slug-tested intervals. This is in reasonable agreement with the postulated closure of fractures at injection pressures of 2.8 to 3.5 MPa.

The four recovery curves that were designated as Type C are shown on Plates 4.7.4-6a and 4.7.4-6b of the manuscript in the format specified by Cooper et al. (1967) for type-curve analysis (applied injection head on an arithmetic ordinate; time on a logarithmic abscissa). In this format, the intermediate decrease of slope that initiates the step corresponds to the convergence head in Figure II.G-1, which was shown above to agree reasonably well with the least principal stress (tensile failure stress) as determined in USW G-3. If an additional step were to result from passing through the head that should initiate shear failure, it should interrupt the curve segment beneath the distinct step, in the approximate head range of 100±50 m. None of the three curves that show nearly complete recovery shows detectable interruption below the principal step, indicating that there was no elastically recoverable shear dilation of hydrologic significance. The apparently small permeability of the zones tested also indicates that non-recoverable shear dilation, if present at all, probably was not hydrologically significant. However, full resolution of the issue as to whether or not inelastic shear dilation has occurred during large-stress slug tests will require testing of previously untested zones. These tests should begin with small initial (positive) applied heads, progress to applied heads of 500 - 700 m, return to applied heads of the initial tests, and conclude with negative applied heads. This sequence should be performed in holes that previously have demonstrated the stepped recovery and, in order to be conclusive, must exhibit stepped recovery during the new tests.

iii. <u>Conclusions on Slug Tests</u>

It is evident from the slug tests in USW H-3 and in several other wells that the stepped-recovery behavior is real. A conceptual understanding can be attained with reference to any of several plates in the manuscript (e.g., 4.7.4-6a). In the initial stage of the slug test, fracture dilation propagates outward along the fracture, causing the fracture hydraulic conductivity and storage capacity to increase as a result of the increasing fracture aperture; the recovery curve is very steep in comparison with the theoretical curves. In the second stage, the average dilated fracture aperture decreases with attendant decreases of the hydraulic conductivity and storage capacity of the fracture; the recovery curve flattens, more so than the type curves at equivalent stages of recovery. The final stage begins when the fluid over-pressure declines to the fracture closure pressure, and the recovery of the fluid pressure proceeds with constant values of hydraulic conductivity and specific storage; the recovery approaches a reasonable match to the type curves. The final stages of recovery are advanced in time relative to the recovery that would have occurred if only the invariant hydraulic properties of the rock had prevailed throughout the test.

The results of both the hydrofrac and slug tests demonstrate that the rock-mechanical and hydraulic stresses are coupled, fully in accord with long-accepted theory in soil and rock mechanics. In this broad aspect, we agree with the manuscript; the heads applied in many of the slug tests exceeded both shear and fracture-separation criteria. However, these criteria are usually exceeded only in a small volume of rock around the borehole (Dougherty and Babu, 1984). It cannot be demonstrated with presently available data that the dilatancy observed in the slug tests can be extrapolated to larger scales than that affected by the small-volume injection. In fact, the comparable results from slug tests and pumping tests combined with flow surveys indicate that the most permeable zones are relatively insensitive to the hydraulic stress, and thus to the effective stress, in tests of this type. We conclude that small-volume injection tests are incapable of demonstrating the larger-scale coupling effects that the author has postulated.

3. POTENTIOMETRIC CHANGES AT YUCCA MOUNTAIN

On Page 4-3 of the manuscript, it is stated that "The most important data, with respect to the conceptual considerations of the flow field are undoubtedly the data which relate values of the hydraulic potentials in the field to time." We would agree that the data have potential significance in providing evidence for long-term (detectable on records over several years) and short-term (days or less) changes of storativity in the saturated rock mass, provided that other factors are given proper consideration in the analysis.

The present observation wells at and near Yucca Mountain are completed as piezometers, in that the water column is unconfined, and most provide only composite levels dominated by the heads in permeable zones. Only a specific set of the wells (the WT-series) penetrate the water table for sufficiently small depths that they provide high-confidence data on water-table altitude. Instrumentation in many of the wells provides continuous recording, in some cases at multiple depths, so that short-term changes can be observed. Long-term monitoring to detect small changes is more problematical. Because of the great depth to water (500 to 750 m), electronic sensing of water levels is necessary for continuous recording and has attendant problems of drift and instrument failure. Barometric and earth-tide effects complicate the significance of periodic wire-line measurements from the surface, as does the achievable precision of the method. Very long periods (decades) may be required to acquire data in which we can have a high degree of confidence.

Therefore, the Project is searching for more stable electronic monitoring systems that would facilitate data processing and would allow the detection of trends in records of shorter duration.

Currently, however, data of sufficient duration, sensitivity, and freedom from instrumental drift are not available to determine whether slight but persistent changes of water-table altitude or hydraulic potential are occurring beneath Yucca Mountain. Further, the author's contention that such changes, if observed, would demonstrate extensional dilation and a consequent increase of storativity ignores other possible causes such as multi-year climatic cycles. However, the attempted detection of such trends and, if discovered, thorough study of the causes and significance are legitimate charges to the Project.

Short-term excursions of water levels on the order of a meter or less may in fact be evident in the existing though unpublished data from wells at and near Yucca Mountain. The data are being evaluated relative to instrumental and atmospheric factors, but the Project has not ruled out the possibility that they are related to tectonic strain of the rock mass. Again, the collection and analysis of these data are acknowledged to be necessary during site characterization.

Although the reviewers judge that strain-reactive hydrologic effects at a scale that is significant in terms of repository performance have not been demonstrated in this manuscript, they acknowledge that the lack of such significant effects from natural earthquakes or rock-mass strain likewise has not been demonstrated. Accordingly, the Yucca Mountain Site Characterization Plan (DOE, 1988) includes studies to address and evaluate the possibility.

H. GEOLOGIC RECORD

If the processes proposed in the manuscript act at rates that would be significant in the isolation lifetime of a repository, the geologic record should contain evidence of former elevated positions of the water table or evidence of hydrothermal upwelling. According to the discussion at the bottom of Page 3-36, the last phase of an "evolutionary loop" in the model for coupled flow of heat and fluid in a deforming fractured medium will be characterized by the cooling of mineralized fluids from depth and the precipitation of minerals from these fluids along fractures. The author hypothesizes that this process gradually decreases the fracture apertures and, ultimately, will completely close and fuse the medium. The stage is then set for another period of gradual extension and pervasive fracturing, beginning another cycle in the "evolutionary loop." This provides a clear and specific prediction from the author's conceptual model: precipitation of minerals from mineralized fluids that rise from depth and cool along fractures in a deforming medium. The manuscript acknowledges that a critical question, therefore, is whether the geologic record representing late Pliocene and Quaternary time contains evidence of fracture mineralization by upwelling of fluids. The author concludes on Page 5-4 that the calcite and opaline-silica deposits in faults near Yucca Mountain are evidence that such a process "is real, and by all means not remote."

In Section 4.8, the manuscript proposes evidence for the cyclic occurrence of these processes in Late Pliocene and Quaternary times. Additionally, it offers evidence and analysis in Section 4.6.4 that calcite veins sampled from drill core at Yucca Mountain formed at temperatures higher than those that are characteristic of the sampled depths at the present time. The proposition that upwelling waters have left persistent mounds in the current vadose zone is examined closely in Section II.E of this review, with the conclusion that the evidence presented, particularly when supplemented with pertinent evidence that was omitted, did not support this interpretation.

This section of the review report begins with a restatement of some necessary precautions in the use of dates established for carbonate deposits; these precautions should be kept in mind during discussion of specific deposits in the field. Next, information relating to near-surface and deeper paleotemperatures is reviewed, along with the treatment of isotope methodology in the manuscript. The specific field occurrences proposed by the author to support his contentions that the water table has been much higher in the past and that it has possibly erupted hydrothermally to the surface are then examined, and additional geochemical observations that are pertinent to the question of past water levels are then presented. Finally, the editors present their understanding of the significance of currently available information.

1. U-SERIES AGES

Many major conclusions in Section 4.8 of the report are based on ages of samples from several localities, determined by the uranium-series (U-series) method of dating. U-series dating is a well established technique for determining ages for certain materials and environments, although its limitations are not yet fully understood. The ages obtained should not be used indiscriminately without due respect for these possible limitations. In particular, uncertainties reported by the original authors along with the ages should not be ignored.

Two of the limitations relate to difficult problems in the processing of samples in the laboratory. First, where detrital fragments and chemically precipitated carbonates coexist, they cannot be completely separated by simple chemical or physical means. Secondly, Szabo et al. (1981) explain: that "dating of impure carbonates that are heterogeneous mixtures of materials with different ages is still tentative because there must be more experimental work to document the validity of the acid leaching process used in this study."

Three limitations result from depositional conditions and post-depositional processes. First, Winograd et al. (1985) indicate that in U-series dating, to rule out initial detrital ^{230}Th contamination, the $^{230}Th/^{232}Th$ activity ratio must be greater than 20. Second, calcite may take up uranium released during the crystallization or recrystallization of contained silica, making the calcite date younger than actual but the silica (generally opal) date older than actual. Finally, as stated by Szabo et al. (1981): "... pure carbonates may be dated by the uranium-series method provided that the samples represent a closed system; that is, there has been no post-depositional migration of uranium isotopes nor their in situ produced long-lived daughter, ^{230}thorium."

Szabo and his colleagues, in the several reports referenced in the manuscript, consistently remind the unwary reader of the limitations that may apply to their reported dates. However, the dates discussed in the manuscript represent only a fraction of the data presented by Szabo et al. (1981) and overemphasize those data to which the above limitations apply.

On Plate 4.8-11, the author omits the large number of samples dated >400 Ka and, for those <400 Ka, does not distinguish those believed by the original authors to be reliable from those to which limitations apply. It is hardly surprising that he concludes that correlation with global climatic cycles is lacking. We propose that, if a correlation between carbonate deposits in the region and climate is demonstrated in the future, the local climate may be at least as influential in the correlation as global cycles.

2. PALEOTEMPERATURES

Isotopic compositions of calcite veins in vadose-zone cores from three drill holes at Yucca Mountain and of calcite samples from Trench 14 on the Bow Ridge Fault and from Fran Ridge are discussed on Pages 4-21, 4-36, and 4-37 of the manuscript. The author interprets them as suggesting, though not proving, that near-surface temperatures at Yucca Mountain have varied through time and that the veins were deposited by "warmer subsurface fluids," both of which are consistent with his conceptual model of heat flow (hydroconvectively) in the deforming fractured medium.

Szabo and Kyser (1985) reported $\delta^{18}O$ and $\delta^{13}C$ compositions as well as U-series ages for the core samples from UE-25a#1, USW-G2, and USW-G3/GU3. Four samples of calcite and four of opal were dated >400 Ka, whereas 10 samples of calcite provided apparently determinate ages between 26 and 310 Ka. Szabo and Kyser suggested that this might indicate vadose-zone percolation during the period of 26 to 310 Ka, and possibly concentrated at approximately 28, 170, and 280 Ka. However, they do not accept all of these calcite ages as determinate. For samples containing opal as well as calcite, Szabo and Kyser (1985) state: "Alternatively, the finite calcite dates may be the result of open system modification. In this explanation all calcite deposits are assumed to be older than 400,000 years. Crystallization of opal then released additional uranium which was incorporated in some of the calcites making them appear too young ... crystallized opal coexisting with calcite exhibits uranium redistribution and possibly uranium loss as a function of recrystallization, but there is no indication of secondary uptake by the lowest-uranium containing host calcite (sample 348.8-A in table 2)." Sample 348.8-A was the only calcite in this suite to be dated >400 Ka.

A principal interest of the publication was to apply isotopic data to establish paleogradients of the thermal field. The gradient was estimated to be about 43°C/km, which Szabo and Kyser (1985) considered to agree well with independent measurements by Sass et al. (1980) using borehole temperature logging in UE25a#1 and UE25a#3. They cautioned that their isotopically determined gradient was a maximum value, as precipitation of carbonate could have depleted descending water in ^{18}O, resulting in overestimates of precipitation temperatures that increase with depth.

Citing O'Neil et al. (1969), Szabo and Kyser (1985) assumed a $\delta^{18}O$ value for meteoric water of -9 °/$_{oo}$, resulting in equilibration temperatures of about 20°C near the surface and about 46°C for a sample from a depth of 611 m. Although they note that Sass et al. (1980) estimated mean annual ground-surface temperature on Yucca Mountain to be about 15°C, they did not discuss the assumed $\delta^{18}O$ of -9 °/$_{oo}$ at UE25a#1, apparently because of their objective of determining gradient rather than absolute temperatures at depth. In a later draft, not yet published, Szabo and Kyser used a $\delta^{18}O$ of -10.5 °/$_{oo}$ in order to duplicate the 15°C surface temperature and recalculated calcite-precipitation temperatures, with a result of about 37°C for the deepest sample and a gradient of 35°C/km. This gradient is about 50% higher than the average (24°C/km) in UE25a#1, USW-G2, and USW-G3/GU3 (Sass and Lachenbruch, 1982). Among the possible explanations are that the error associated with carbonate precipitation has caused an overestimate of the gradient, or that the calcite did not form under the contemporary conditions that the calculation attempted to duplicate. (See the discussion below regarding more probable values for $\delta^{18}O$ in water during the past 250 Ka.)

In the manuscript, the precipitation temperatures were determined from Plate 4.6.4-4 (from Szabo and Kyser, 1985, Figure 7), without questioning the assumed value of -9 °/$_{oo}$ for $\delta^{18}O$ in the source waters despite the repetition of this assumption in the caption of the figure in Szabo and Kyser (1985). The author then plots (on Plate 4.6.4-6) the temperatures against depth, adds the contemporary thermal profiles from three boreholes, and concludes (Page 4-21) that "Differences between the contemporary and the in situ paleo-temperatures are substantial ranging from a few °C near the ground surface to as much as 15°C at a depth of about 600 meters [and] it is possible that at the onset of a new evolutionary loop of the system the values of geothermal gradients are 5 to 15°C per km higher than at the end of this loop."

Calcites sampled from the vein in Trench 14, occurring in the Bow Ridge fault, and from caliche along Fran Ridge (mis-identified as a vein sample in the manuscript) are discussed on Pages 4-36 and 4-37. The author plotted (Plate 4.8-3) the isotopic data of O'Neil (written communication, 1984) on Figure 7 from Szabo and Kyser (1985), thereby estimating temperatures referenced to a source with $\delta^{18}O$ of -9 $^{o}/_{oo}$. The apparent temperatures for the three samples, which are very similar with respect to both ^{18}O and ^{13}C, ranged from 24 to 27°C or, according to the author, 5 to 8°C higher than the contemporary temperature of rock near the ground surface. (The calculated range is actually 21.4 to 24.7°C; the author apparently determined the temperatures only graphically from Plate 4.8-3.) He concludes (Page 4-37) that "This may suggest, but does not prove, that warmer subsurface fluids are responsible for deposition of the calcite-silica veins."

The author analyzes and draws conclusions from isotopic data but does not question the underlying assumption, which is quite in contrast with $\delta^{18}O$ values of -12.7 to -13.7 $^{o}/_{oo}$ for vadose-zone water at Rainier Mesa (Russell, 1987) as shown on Plate 4.7.3-9. In fact, O'Neil (written communication to D. Vaniman, 1984, made available to the author at the Calcite-Sepiolite Veining peer review meetings), in transmitting his data that are discussed in the preceding paragraph, expressed his current preference for using $\delta^{18}O$ of -13$^{o}/_{oo}$ for making calculations of paleotemperatures from isotope data for calcites from this region; the manuscript neither discusses nor acknowledges this preference. Importantly, groundwaters with ^{14}C ages of modern to 30 Ka yield $\delta^{18}O$ of -12.4 to -13.8 $^{o}/_{oo}$ (Claassen, 1985), and data for deuterium (which varies in a linear fashion with oxygen isotopes in most waters) in fluid inclusions of spring deposits suggest that such values have prevailed in the groundwater for at least the past 250 Ka (Winograd et al., 1985). Recalculation of the temperatures at which the calcite samples formed, using more current estimates of source $\delta^{18}O$, -12.4 to -13.8 $^{o}/_{oo}$ (Claassen, 1985), than were available to Szabo and Kyser (1985) when their report was prepared, provides surface temperatures from 2 to 17°C for most of the samples and 20 to 27°C for the deepest sample (611 m). This range is consistent with an origin for the calcites by precipitation from infiltrating water in a climate cooler than today's.

The difference between upwelling and downflowing origins is extremely significant, yet the manuscript fails to address the possible source of upwelling water. The overwhelming dominance of calcite in the fault and fracture fillings requires a source for the hypothesized mineralized fluids that has an abundance of calcium carbonate. As the Precambrian rocks (except for the uppermost Precambrian Noonday Dolomite) and Tertiary rocks near Yucca Mountain lack significant thicknesses of carbonates, the most obvious choice as a potential source is the thick (kilometers) sequence of Paleozoic limestones and dolomites. These rocks comprise the regionally extensive "lower carbonate aquifer" of Winograd and Thordarson (1975) and, in addition to calcium carbonate, are capable of supplying an abundance of water. Where penetrated near Yucca Mountain in drillhole UE-25p#1 at a depth of about 1,200 m (Carr et al., 1986), the aquifer yielded water of 54 to 57°C (Craig and Robison, 1984; Sass et al., 1988). Benson and McKinley (1985) report bicarbonate-dominated water with a $\delta^{13}C$ value of -2.3 $^{o}/_{oo}$ from the lower carbonate aquifer in UE-25p#1. The $\delta^{13}C$ values for the calcites, <-4 to <-8 $^{o}/_{oo}$, might seem to preclude precipitation from water having a $\delta^{13}C$ of -2.3 $^{o}/_{oo}$. However, Claassen (1985) reports $\delta^{13}C$ values of -5 $^{o}/_{oo}$ from Fairbanks

Spring at Ash Meadows and of -4.6 $^{o}/_{oo}$ from a well in the eastern Amargosa Desert, both discharging from the lower carbonate aquifer. More analyses and possibly more data will be required before this line of evidence could eliminate the lower carbonate aquifer in the Yucca Mountain area as a source. The analyses must include consideration of isotope fractionation during precipitation for reasonable ranges of source-water chemistry, pH, and temperature, unless other diagnostic constituents are found to unambiguously evaluate proposed sources of the water.

On Pages 4-37 and 4-38, the manuscript explicitly (though tentatively) attributes the origin of the calcite in the core samples from the boreholes to upwelling fluids. It would seem very coincidental that 57°C (or warmer) water would rise to such diverse heights and locations as are represented by the surface at the Bow Ridge and Fran Ridge sampling sites and by the shallowest samples in the three boreholes, cooling in each case to the narrow range of 20 to 25°C proposed by the author.

There is, however, evidence of much larger thermal gradients at Yucca Mountain during the Miocene Epoch. Bish (1987) has discussed the paleothermal regime based upon clay-mineral assemblages and potassium-argon dating. Low paleotemperatures are interpreted for the southern end of Yucca Mountain (<100°C, below about 1,000 m), but they increase to the north (>275°C, below 1,000 m). The alteration has been dated consistently at 11 Ma in cores from three drill holes. The northward increase of paleotemperatures is also consistent with the location to the north of the Timber Mountain and Claim Canyon calderas, which were the eruptive source of the Paintbrush (12.5 Ma) and the Timber Mountain Tuffs (11.3 Ma). The Timber Mountain caldera cycle records the last major thermal event known to have occurred at or near Yucca Mountain.
The isotopic, mineralogic, and paleothermal data that are currently available are insufficient to disprove that the vein calcites were deposited from upwelling fluids; however, with the same interpretive uncertainties, the data suffice to establish with reasonable confidence that they were deposited from infiltrating meteoric water.

3. CALCITE AND OPALINE-SILICA (HYDROGENIC) DEPOSITS

The calcite and opal deposits in this region are highly significant to an evaluation of the author's conceptual model. Most of the discussion of the calcite and opaline-silica deposits is on Pages 4-35 to 4-40 of the manuscript and consists of geologic and isotopic observations and interpretations. The author reports little of the pertinent petrologic and mineralogic information. Most of the following information was presented to Project working groups on fault-related calcite and opaline-silica deposits near Yucca Mountain and, later, to a panel of independent peers (Voegele, 1986a, 1986b; Blanchard, 1987). Access to all of the data that are described below was available in the Project Office in Las Vegas at the time that this manuscript was in preparation, and the author attended most of the review sessions.

a. Breccias

The manuscript states on Page 4-36 that "silica-cemented breccias" commonly form the wallrock of the calcite and opaline-silica vein deposits near Yucca Mountain and that they are clearly older than the veins. In some places, secondary calcite replaces tuff fragments and, together with opal, also occurs in the cement. That the breccias are older than the calcite and opaline silica is not disputed; in fact, several investigators tentatively consider them to be synvolcanic, (i.e., late Miocene). However, silica-cemented breccias form only a part of the wallrock in Trench 14 (Bow Ridge fault) and in Trench 8 (Solitario Canyon fault). In fact, in Trench 14 the breccia is dominantly calcite-cemented with lesser opal in voids (Vaniman et al., 1988; reported also during the 1987 peer review). In the other occurrences, along the Paintbrush Canyon fault and an unnamed fault on the west side of Busted Butte, the breccias are partly concealed by younger surficial deposits and do not clearly occur as the wallrock of the calcite and opaline-silica deposits. The breccias underlie eolian deposits at both of these locations. At Busted Butte the age of the breccias is constrained by the fact that they are overlain by an ash which in turn is overlain by eolian deposits. The ash is interpreted to be the Bishop ash, which has a well documented age of 740 ± 10 Ka based on $^{40}Ar/^{39}Ar$ and K-Ar dating at numerous localities (Hurford and Hammerschmidt, 1985). Thus, the silica-cemented breccia at Busted Butte is older than 740 Ka.

The author reports the breccias to be tens of meters to several hundreds of meters in thickness (Page 4-36). Project scientists expect that the greater breccia zones may indeed be as much as tens of meters wide in some cases, while the most intense and obvious brecciation is typically 1-2 m wide (Oral Communication, S. Levy (LANL) to D. Vaniman (LANL), June 1, 1989).

The evidence that these are "explosion" or "fragmentation" breccias (Pages 4-35 and 4-36) is ambiguous. An explosion breccia of hydrothermal origin has indeed been suggested (Mattson, 1986; Hanson, 1987), but other hypotheses have also been offered, such as rubble infillings of near-surface fault openings. Fractures filled by in-blown sand and ash at Trench 14 attest to episodic opening of the Bow Ridge fault. Silica-cemented breccias are common in ash-flow tuffs and other silicic volcanic deposits. The exact origin of these breccias is not known, but they are thought to occur in association with hydrothermal activity during eruptive and caldera-forming events (Hulen and Nielson, 1988; Nelson and Giles, 1985). Events of this type occurred near Yucca Mountain 11 to 14 Ma. Clearly, more work is needed to assess the significance of the silica-cemented breccias. However, their origin may be irrelevant to repository performance, although of scientific interest, if it can be demonstrated with better exposures or age determinations that they are synvolcanic or that they formed in the earliest stages of late- or post-caldera development of the north-trending faults.

b. Calcite Deposits Near Yucca Mountain

Deposits of calcite, commonly containing associated opaline silica, that occur in association with faults near Yucca Mountain, including the vein in the often-visited Trench 14 on the Bow Ridge fault, are generally considered to be the most compelling evidence in support of the author's model. A statement on

Page 4-35 could mislead a reader who is not intimately familiar with the locality and the work that been done: "The calcite-silica deposits ... also occur as aprons developed over the unconsolidated alluvial and eolian sediments." This brings to mind visions of travertine terraces draped over the surface, such as those visible at Travertine Point along Furnace Creek in Death Valley. Detailed mapping in the Yucca Mountain area has not identified any deposits fitting this description at the surface or in exposures of now-buried paleosurfaces. In fact, the absence of remnants of aprons or terraces at the sites of acknowledged vein deposits is a strong line of evidence that discharge to the surface did not occur. The well preserved terraces along Furnace Creek occur in association with veins that are reliably dated at ~1 ± 0.1 Ma (Winograd and Szabo, 1986).

The calcite and opaline-silica deposits are discussed as being associated with Late Pliocene to Quaternary faults and with Late Pliocene to Holocene surficial deposits. In fact, the faults are old faults (Tertiary) which in some instances have been reactivated, with minor offset, in the Quaternary. The youngest deposits that are truncated by the vein calcites include late Pleistocene surficial deposits. Basaltic ash (infilling from above into cracks as a result of faulting) is found in some of the veins. The ash postdates most, if not all, of the deposits located along fault zones and as such represent a minimum age of the deposits. The author concedes (Page 4-36) that the age of these ashes may be as much as 1+ Ma; tephrochronologic studies have so far been unable to differentiate between the late Pleistocene (possibly Holocene) ashes from the Lathrop Wells basaltic center and the older (~1.2 Ma) ashes erupted from central Crater Flat. Because the fissures cut late Pleistocene surficial deposits, the ash was probably derived from the Lathrop Wells center, which was active during and after late Pleistocene time. The limited extent (a few kilometers) of the latest (Holocene?) ash from this center, however, suggests that it did not not provide the fissure fillings.

Although Szabo and O'Malley (1985) are cited elsewhere in the manuscript, their data relevant to the age of the Trench 14 deposits are not presented. In their publication, U-series dates from three opal samples and one calcite sample from Trench 14 alluvium are given, consistently, as >400 Ka. However, the vein deposits do cut alluvial deposits that have been dated by the experimental U-trend method at 420 ± 50 Ka (Swadley et al., 1984). There clearly is a need for additional dating of the veins and associated deposits.

Implications in the draft (Pages 4-36 and 4-37) as to the paleothermal significance of the $\delta^{18}O$ and $\delta^{13}C$ data of Szabo and Kyser (1985) were discussed previously in Section II.H.2. The reader will recall that the manuscript uses, without challenge, a source-water value of -9 $^{o}/_{oo}$ for $\delta^{18}O$ and graphically derives a range of 24 to 27°C (about 2°C higher than those calculated with the same assumptions) for the precipitation temperature of the calcites. However, there is abundant evidence supporting a range of -12.4 to -13.8 $^{o}/_{oo}$ for $\delta^{18}O$ in groundwater of this area ranging in age from modern through Pleistocene (O'Neil, 1984; Claassen, 1985; Winograd et al., 1985; Russell, 1987). Use of this range for water results in a calculated range of 2 to 17°C for surface temperatures at the time that the calcites were precipitated.

The manuscript incorrectly describes sample FR-6 as "representing the veins from the Fran Ridge fault" (Page 4-36) when, in fact, FR-6 is a soil caliche sample (Vaniman et al., 1985). Vaniman et al. state that "isotopically, there is no basis for assuming that there is any difference between soil-zone calcite of the sand ramps (FR-6) and calcite deposited within the fault at Trench 14 (T-14fb, T-14-3a-w)." From the author's interpretation as summarized above, FR-6 and the other near-surface samples formed at temperatures 5 to 8 Celsius degrees higher than the present-day temperature. However, because this sample is known to be pedogenic, its similarity to the vein calcites, in terms of both oxygen and carbon isotope compositions, has been used to infer that the veins may also be of pedogenic origin (Vaniman et al., 1988).

In their memo to Veith, Vaniman et al. (1985) also compare the soil-zone mineralogy of the sand ramps around Yucca Mountain with the mineralogy of fault deposits. Their Figure 1 exhibits X-ray diffraction patterns of soil-zone deposits from the sand ramp at Fran Ridge (FR-6) and fault deposits exposed in Trench 17 (Tr-17). Both patterns are very similar and show assemblages dominated by calcite and opal-CT (opal with mixed cristobalite and tridymite types of structures) with lesser quartz and sepiolite. (The quartz was not formed in these veins; rather, it is a detrital material that apparently has fallen into an open fault.) Thus, the soil-zone and fault deposits contain virtually identical mineralogical assemblages. Based upon the directly comparable mineralogy of the sand-ramp soils and fault-related samples, and upon the isotopic similarity of the calcites, there is no reason to conclude that the geochemical processes responsible for the fault-related minerals are significantly different from those giving rise to the soil-zone and sand-ramp minerals.

Finally, the statement in the concluding section of the manuscript (Page 5-4) that "detailed studies of the calcite-silica-sepiolite vein deposits, however, were not performed" is incorrect, as is evident in the discussion above.

c. **Wahmonie**

Wahmonie, which is discussed on Page 4-39 of the manuscript, is the only locality where gypsum is known to occur near Yucca Mountain, although a statement on Page 4-38 might imply to some that gypsum is common in the area. A "recent" origin for the surface deposits at Wahmonie was, in fact, stated in the draft Yucca Mountain Environmental Assessment (DOE, 1984) as claimed, but it was deleted from the final Environmental Assessment (DOE, 1986) because the statement could not be substantiated. Alteration of tuffs and geophysical evidence (gravity and magnetics) support the existence of a shallow intrusive body in this area, but the age is not well defined. Investigation of the Wahmonie site is warranted, though in a phased approach that first evaluates whether the deposits are young enough to suggest the possibility of their recurrence in the geologically near future.

d. **Cane Spring Fault**

By the omission of comment on the Winograd and Doty (1980) interpretation that calcite veins at their sampling Site 4 on the Cane Spring fault were not precipitated within a regional zone of saturation, and by stating their proximity to the groundwater mound proposed to occur near Skull Mountain, the manuscript implies that they are related to groundwater mounding (Page 4-39 of the manuscript; the reference should be to Plate 4.2-3, not 4.3-3). Based on the information presented, the reviewers see no reason to consider these veins to be different from those occurring near Yucca Mountain (i.e., unlikely to have been formed by upwelling water). The evidence for the proposed Skull Mountain mound was evaluated previously in this review, with the conclusion that water chemistry precluded origin of the perched zone or zones from upwelling water.

e. Crater Flat

The "spring mounds" described by Hoover et al. (1981) near the southern end of Crater Flat are not labeled on Plate 4.8-5, but the manuscript implies that they include both localities 106 and 199 of Szabo et al. (1981), which these authors dated as 78 ± 5 Ka and "~30,000" years. The author does not acknowledge the tentative nature of the reported U-series dates for these deposits. Szabo et al. (1981) caution: "Tufaceous travertines [i.e., sample 199] may occasionally form open systems with respect to uranium and thorium, and hence those results may indicate minimum ages only. Calcretes [i.e., sample 106], likewise, have some degree of uncertainty wherein determined ages may reflect minimum ages, but under favorable conditions, can yield reasonable ages for the time of cementation of the deposit."

In Szabo et al. (1981), sample 106 is described as a "seep-deposited tufa or calcrete intercalated in Q2 alluvium ... exhibits some evidence of spring-water deposition." The sample is interpreted as "Giv[ing] approximate minimum age of Q2 alluvium..." and is dated at 78 ± 5 Ka. The sampling locality is on the low divide between southern Crater Flat and Fortymile Wash along the southward extension of Yucca Mountain. The manuscript states that the deposit occurs "at an altitude of about 940 meters, ...about 200 m higher than the altitude of the contemporary water table" (Page 4-37). The author leaves the conclusion to be drawn to the reader.

We attach significance to Szabo et al.'s description of sample 106, in that the age is probably a minimum value. More importantly, however, their use also of the term, "seep-deposited", precludes any perception that they believed the deposit to record significant spring flow. Within the region, the interstratification of poorly and moderately permeable tuffs leads to numerous perched water bodies that seep slowly at small, seasonal springs such as Cane Spring and Topopah Spring. The possibility that the deposit from which sample 106 was obtained represents a perched seep merits more detailed hydrogeologic study of the locality, unless concurrent evaluation of Szabo et al.'s (1981) alternative of a pedogenic calcrete proves to be affirmative.

Sample 199 is described (Szabo et al., 1981) as a "Nodular tufa spring deposit, south end of Crater Flat" and is dated at "~30,000" years. The interpretation given for the sample in the report is: "suggested spring activity was at altitude of 838 m as late as 30,000 yrs. ago. Present water table [see discussion below] is about 120 m lower." Documentation of the rationale for labeling these as spring deposits is not provided, but the judgment is probably correct. The tufa is associated with marsh or pond sediments. Ostracodes found in similar marsh deposits about 3 km to the south, near highway US 95, provide especially useful information in that they are unlike those that live in spring-discharge areas of the regional aquifers, are typical of "temporary (i.e., seasonal)" water bodies, and may indicate a perched cold "but not frigid" spring origin. Thus, they may have formed at any distance above the water table (Forester, 1979; 1988). The small sizes of the deposits are also consistent with formation in seasonal springs or ponds.

The depth to the current water table (120 m) beneath site 199 that was suggested by Szabo et al. (1981) represents a water-table altitude of about 720 m. It was probably based on published potentiometric-surface maps that were prepared before the exploration of Yucca Mountain and Crater Flat provided additional water-level information. Whereas the water level in Roses well, in the Amargosa Desert 4.4 km south of site 199, is at an altitude of 711.5 m (Winograd and Thordarson, 1975), that in drill hole USW VH-1, 7.5 km to the north of site 199, is 780 m (Robison, 1984). The assumption of a linear gradient would provide a predicted altitude of 740 m beneath the apparent tufas. The marsh-like sediments associated with the tufas, however, are mapped (Swadley and Carr, 1987) in a channel west of the tufas up to an altitude of about 854 m. We can thus conclude that, if the deposits represent discharge from the water table rather than perched springs, the water table beneath southernmost Crater Flat was at least 100 m, and perhaps 115 m, higher than at present.

The age of the discharge at site 199 is quite obviously of interest. The samples were described earlier as mid-Pleistocene by W.J. Carr (Forester, 1979). Most, though not all, reviewers considered that the expression of the analytical age as approximate, rather than in terms of standard error, implied an age much greater than a minimum of "~30,000" years reported by Szabo et al. (1981). Assuming contemporaneity of the tufas and detrital sediments, overlap of a widely recognized alluvial unit (QT2c) indicates an age of at least a few hundreds of thousands of years. Vertebrate, diatom, and ostracode fossils from the possibly correlative deposits near highway US 95 support an older age assignment, but they do not prove it, and no non-calcite datable materials have been found at site 199 itself. Because these and similar deposits in the Amargosa Desert are small and widely separated from each other, stratigraphic correlations are complex, involving the relation of the probable marsh deposits to more widespread and datable units. By means of such correlations, Swadley and Carr (1987) consider the deposits to be largely of Pliocene age; they suggest an age of "less than 2 m.y.", based on mammoth remains, for the uppermost beds of the US 95 deposit, which is at the northern limit of the Amargosa Desert at an altitude of 800 m.

f. **Furnace Creek**

The Furnace Creek veins are presented (Pages 4-39 to 4-40) as an analogy to the calcite and opaline-silica deposits that occur near Yucca Mountain. The Furnace Creek veins are composed only of coarse-grained, sparry calcite, and, in this regard, are distinct from the silica-rich and fine-grained deposits located along faults near Yucca Mountain. The Furnace Creek veins are coarse-grained up to within a few meters of the surface (including the tufa mounds), where they grade to a mixture of fine-grained and subordinate coarse-grained textures. The differences in mineralogy and texture between the Furnace Creek deposits and those located near Yucca Mountain suggest different depths of exposure, different origins, and different water chemistries.

The discussion in the manuscript states (Page 4-40) that the radiometric dates on samples of the Furnace Creek veins are as young as 100 Ka. This date is very important, as the author develops the premise that 100,000 yr is too short a time period for tectonic movement to account for the elevation of the deposits above the present water table; therefore, tectonic mounding of the water table is indicated. However, the citation (Winograd et al., 1985) assigns 100,000 yr as the lower end of a range for deposits in a different locality. With respect to the Furnace Creek veins, Winograd and Szabo (1986, Page 7) state "groundwater flow in the fracture containing this vein ceased ~1 ± .1 Ma" A million years is adequate for the tectonic processes described by Winograd and Szabo (1986), including absolute uplift of the Funeral Range and the Sierra Nevada, the latter causing increasing aridity, to have left evidence of groundwater discharge at the present altitude of the Furnace Creek veins.

4. GEOCHEMICAL EVIDENCE OF WATER-TABLE ALTITUDE

The manuscript does not consider much of the geochemical information that is pertinent to former positions of the water table and to past groundwater movement at Yucca Mountain. For example, Zielinski et al. (1986) show that uranium has been mobilized (microns to centimeters) by the passage of water through the currently unsaturated tuffs. They conclude that mobilization must have occurred more than 400,000 years ago, and thus likely precludes any elevated groundwater at Yucca Mountain since then.

Bish and Vaniman (1985) observed that nonwelded glass occurs both above and below the welded zone in the Topopah Spring Member (Tptw) of the Paintbrush Tuff at Yucca Mountain. These authors state "the lower nonwelded vitric zone thins and disappears to the east where stratigraphic dip and structural displacement bring the basal Tptw glassy zone closer to the [water table]. The vitric nonwelded material may have important paleo-hydrologic significance because the preservation of open shards and pumice [in] a nonwelded glass is rare below past water levels (Hoover, 1968)." Where present, the base of the lower nonwelded vitric tuff occurs 80 to 100 m above the present water table. On the basis of mineralogy, Bish and Vaniman (1985) concluded that "The only apparent change in phase assemblage near the water table in Yucca Mountain is the alteration of the vitric tuff in Calico Hills and lower Topopah Spring Member." Project scientists do not agree unanimously with these tentative conclusions, because glass shards are preserved far beneath the water table in drill hole UE25p-#1. However, there are plans for additional petrographic studies, for example, with respect to possible protection of the glass shards by cristobalite armoring. Nonetheless, unequivocal mineralogical indications of past positions of the water table remain elusive.

On Page 4-38 the manuscript states that a 33 m thickness of metasomatically altered tuff has been found in drillhole UE-25p#1. Carbonate alteration, not metasomatic alteration, was described by the original authors (Carr et al., 1986). The altered and cemented zone is in the basal section of the Tertiary, directly over the fault-zone contact with Silurian dolomites (Carr et al., 1986). As reported by Craig and Robinson (1984), there was an abrupt 20 m rise of the fluid level in the borehole upon penetrating the altered zone. It seems likely that upward leakage through the fault was responsible for the mineralization and that it ultimately sealed its own pathway. No particular significance should be assigned to the fact that the hydraulic potential is higher in the Paleozoic aquifer than in the overlying Tertiary rocks. This is consistent with our understanding of the regional hydrology. Yucca Mountain is approximately midway along the flowpath from recharge areas to discharge areas, in the transition zone from a regionally average decrease of head with depth to a regionally average increase of head with depth.

Carbonate alteration is locally common at Yucca Mountain and may be pervasive at some localities (Bish and Vaniman, 1985; Chipera and Bish, 1988; Bish and Chipera, 1989; Diehl and Chornack, in prep.). It is typically associated either with vapor-phase activity of a cooling ash-flow sheet or with alteration of tuff in the presence of carbonate-charged fluids. Based on clay mineralogy in UE-25p#1, Chipera and Bish (1988) estimated a temperature of 175°C for a clay alteration correlated to the 11 Ma Timber Mountain volcanism. That this area was tectonically, mineralogically, and hydrologically active during the Miocene is neither surprising nor of concern.

5. SIGNIFICANCE OF GEOLOGIC EVIDENCE

The reviewers concur with the judgment of the author that the geologic record probably holds the evidence needed to evaluate whether the processes that he postulates have acted in the past within a tectonic and hydrologic environment similar to that existing today and likely to exist during the next 10,000 yr. Much of the record is contained in samples of calcite from the subsurface and near-surface, but, unfortunately, this record has been partly obscured by geochemical processes during and after precipitation of the calcite.

The violent tectonic, geothermal, and hydrothermal environment during the silicic volcanism at the northern edge of Yucca Mountain did not persist after the Miocene, based on field relationships and on geochemical evidence from many boreholes and outcrops (Bish, 1987; Chipera and Bish, 1988). Details of the Pliocene and Pleistocene epochs are less clear, but they suggest discharge of small, perhaps seasonal springs at an altitude of about 840 m in southern Crater Flat and possibly perched seepage at an altitude of 940(?) m on the divide between southeastern Crater Flat and Fortymile Wash. If we assume that the Plio-Quaternary system was hydrogeologically similar to that existing today, though at times influenced by the increased flux of a cooler and possibly wetter climate, we can compare the sparse geologic evidence with hydrologic predictions of the effects of increased flux. An understanding of these effects is needed to evaluate whether climatic causes are a viable alternative to the tectonic processes postulated by the author to have left geologic evidence for a higher water table in the vicinity of Yucca Mountain.

Czarnecki (1985) presented the results of preliminary two-dimensional modeling of water-table rise beneath Yucca Mountain and vicinity, as reported also in the Environmental Assessment for Yucca Mountain (DOE, 1986). Czarnecki simulated the effects of doubling the precipitation in the groundwater subbasin, estimating that average recharge, and hence average flux, would be increased by a factor of 15. The simulation predicts that this recharge would produce a 130 m rise of the potentiometric surface beneath the proposed repository site at Yucca Mountain. The average groundwater flux in the vicinity of the site increased only by factors of 2 to 4. The large gradients toward the site from the north and the west increased only about 10 percent, indicating very small increases of flux across the barriers that are evident in the present potentiometric surface. Transmissivity was constant in the model despite the simulated increase of saturated thickness, so the simulated adjustment of gradient is believed to be conservatively high. These results indicate that the 130 m rise beneath the site is likely about the maximum that could be expected from the assumed increase of recharge.

Based on what is currently known about the distribution of Plio-Pleistocene marsh or pond deposits in the northern Amargosa Desert, water in the highly transmissive alluvium and welded tuffs beneath western Jackass Flats, in the vicinity of Fortymile Wash, probably discharged at altitudes of about 800 m. Allowing an additional 10 to 50 m to establish a gradient from Yucca Mountain to the mouth of Fortymile Wash, at the northern edge of the Amargosa Desert, provides an estimated water-table altitude of 810 to 850 m, or 80 to 120 m above the current water table. This is consistent with independent, though currently equivocal, geochemical evidence that the water table beneath Yucca Mountain in post-Miocene time has not been more than 100 m, and probably less, above its present level.

The postulated contemporaneous occurrence of the water table at altitudes of about 840-855 m in southern Crater Flat, about 800 m in the northern Amargosa Desert, and 810-850 m at Yucca Mountain bears on another issue that has not yet been examined in this document. The water table is both deep and flat beneath central Yucca Mountain (the proposed repository area), but there are strong gradients from higher positions of the water table to the north and west of central Yucca Mountain (Robison, 1984), indicating hydraulic barriers such as faults, rocks of much lower fracture transmissivity, or other causes, whether durable or temporal. The security of these barriers during tectonism in the future seems to have been questioned implicitly on Page 4-14 of the manuscript, and it has been questioned by others as well. During the Plio-Quaternary, the water table beneath central Crater Flat was higher than that in southern Crater Flat and, directly west and north of central Yucca Mountain, it probably was much higher. Consequently, the evidence tells us, though very tentatively, that the hydrogeologic reasons for the present-day steep gradients were operative during that time and that the barriers are likely to remain effective well into the future.

Recall also that Winograd and Szabo (1986) concluded that there was a progressive lowering of the water table in the south-central Great Basin during the Quaternary based on mineralogy and dating of vein deposits, water-table and potentiometric altitudes, and other field observations. They attributed this to tectonic lowering of Death Valley and uplift of the Sierra Nevada,producing a more arid climate to the east. They further speculate that "a continued progressive decline of the regional water table in the next 10^5 to 10^6 years (and beyond?) in response to increasing aridity and to lowering of groundwater base level" is likely. Careful evaluation of this hypothesis is warranted, as it has the potential for markedly increasing our confidence that the return of climatic conditions similar to those of the Plio-Pleistocene will not cause significant rise of the water table beneath Yucca Mountain.

The calcites occurring at altitudes above about 840 m almost certainly were precipitated within the unsaturated zone from infiltrating meteoric water, from the discharge of perched springs, or, as the manuscript advocates, from fault-localized, upwelling of water from deep sources. If we assume, for a moment, that the last origin is correct, then each discharge episode must have been brief in order to allow its surficial deposits to erode so that they would not accumulate sufficient thickness to be preserved at the surface today, just enough to form massive calcite veins, but never enough to form durable surface terraces of travertine. The delicate balance of conditions required to repeat this over and over again, at the diverse spatial locations of the vein deposits at the surface and in boreholes high on Yucca Mountain, and precipitating calcite in the narrow temperature range of 20 to 25°C from water starting its upward journey at 57°C or higher seems considerably beyond the limits of credibility. More work remains to be done, however, before sufficient information is accumulated to choose unambiguously among the alternatives with a high degree of confidence.

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