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EXTERNAL REVIEW PANEL MAJORITY REPORT

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A Review of

"Conceptual Considerations of the Yucca Mountain Groundwater System with Special Emphasis on the Adequacy of This System to Accommodate A High-Level Nuclear Waste Repository"

dated July 26, 1989

by Jerry S. Szymanski

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FINAL REPORT
EXTERNAL REVIEW PANEL MAJORITY

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SUMMARY

An external panel of five members was formed to review reports and proposals by J. Szymanski of the Department of Energy. Quite differing opinions developed within the panel which resulted in preparation of majority and minority reports. The majority (Powers, Rudnicki, Smith) reached consensus on our positions, overall evaluation, and recommendations, and we report them here.

Szymanski has proposed that tectonic activity controls hydrogeological processes at Yucca Mountain, causing cyclical changes in hydraulic properties of the rocks and both discharge of upwelling fluids at the ground surface and saturation of parts or all of the present-day unsaturated zone. As a consequence, Szymanski believes the Yucca Mountain site is unlicensable.

Szymanski's concept of tectonic control of the hydrogeologic system can be described in terms of seven processes: mantle convection, cyclic variation in the *in situ* stress field, temporal variation in the field-scale hydraulic properties of the tuffs, dilatant zones at focal depths that give rise to seismic pumping, episodic wall rock separations of large magnitude, vein and calcrete formation by upwelling fluids, and transient hydrothermal convection. The consequences of each process, and the evidence presented by Szymanski in support of each process, are summarized in section 3 of our report.

Certain elements included within Szymanski's conceptual model address issues that require evaluation during site assessment. These issues are: 1) the spatial and temporal dependence in the hydraulic properties of the tuffs, originating from changes in the *in situ* stress field over a time frame corresponding to the earthquake recurrence period, 2) pressure transients generated as a consequence of strain readjustments following seismic rupture, and 3) deep-seated hydrothermal convection within the through-going faults. Szymanski is correct in isolating these issues as important ones to be considered when characterizing large-scale groundwater flow at Yucca Mountain.

With respect to the specific proposals made by Szymanski, he has developed neither an adequate theoretical basis for the mechanisms and consequences nor a body of evidence that is sufficiently supportive to require further investigation specific to his concepts. We find no basis for the idealization of a deforming fractured medium

adopted by Szymanski. The concept of sudden large wall rock separations on faults, essential in Szymanski's ideas, has not been established, and it is not supported by experience or other evidence. Temporal and spatial changes in the *in situ* stress through the proposed tectonic cycle are considered to explain variable groundwater elevations in the Yucca Mountain area, but the data base supporting the stress distribution is very weak. Calculations presented by Szymanski are inadequate to support his claim about the magnitudes and volumes of fluid movement that could lead to a tectonically-induced rise of the water table. There is no convincing evidence to support his claim that the lithostratigraphic framework can be relegated to a role of minor or no importance in influencing rates and patterns of groundwater flow or when interpreting field data.

Surficial deposits cited by Szymanski as evidence of upwelling fluids are consistent in isotopic and physical character with surficial, pedogenic processes; these deposits are not consistent isotopically with known groundwater in the area of Yucca Mountain. The panel majority sees no reason to reject surficial sources of calcite and silica to account for these deposits. Current data are inadequate to identify recurrence intervals for formation of the calcite and silica vein deposits, should conditions leading to their formation be episodic.

A major flaw in Szymanski's reports is that he has not cast his proposals in any testable forms. It is not apparent that any physical or chemical evidence could be inconsistent with the range of processes and effects claimed within Szymanski's report or in discussions with him. As a consequence, we recommend only one test which directly bears on Szymanski's proposals. We recommend extending Trench 14 upslope, at shallow depths, from its present position to verify the presence or absence of carbonate/silica deposits with indicators of higher temperatures and no biogenic alteration of stable isotopes. Such deposits should mark the pathway for upwelling fluids alleged by Szymanski to have formed the Trench 14 carbonate/silica deposits. This test should be carried out only if Szymanski maintains his position that the fracture/fault at Trench 14 is not the direct pathway.

There are issues related to the tectonic influence on Yucca Mountain hydrologic systems that merit further and pointed investigations. We recommend that a summary of the paleohydrogeology of the present-day unsaturated zone be given high priority. Such

a summary should prove very helpful both for technical studies and management activities, and it should be revised as sufficient data become available. The vein and fracture fillings throughout the unsaturated zone require further detailed study as they are an important record of hydrogeologic processes at the site.

We also recommend a number of studies to resolve other important issues related to site suitability: coordinate studies of the cause of the steep water table gradient at Yucca Mountain; establish a surface strain monitoring network; obtain additional measurements of *in situ* stress in boreholes; investigate short-term fluctuations in downhole transducer records and their possible relation to changes in fluid pressure and *in situ* stress; characterize hydraulic parameters over shorter intervals in boreholes; refine estimates of the extent of the potential water table rise due to seismic rupture and the onset of hydrothermal convection; obtain accurate borehole measurements of subsurface temperature undisturbed by borehole effects; develop summaries of site suitability topics useful to both investigators and managers; and characterize rates of deposition of surface-parallel calcite/silica deposits.

We do not doubt that various aspects of the tectonic setting of Yucca Mountain have affected its hydrogeology and must be considered in model and performance assessment studies. We do not believe Szymanski has established the basis for the magnitude of fluid movement into and through the unsaturated zone that he has stated will occur. Neither has he suggested any means for real testing of the ideas he has proposed explain phenomena at Yucca Mountain.

1.0 INTRODUCTION

1.1 General

The external review panel was formed in 1990 for the specific purpose of reviewing a report prepared by J. Szymanski of the DOE. The panel was asked to make recommendations to the DOE concerning the validity of concepts presented by Szymanski and to make recommendations for further studies. Additional documents prepared by Szymanski during the course of our review have also been considered. Because the circumstances of the panel formation are unusual and the issues are important, we provide some panel history and background to assist the reader in evaluating our report.

The external review panel of five members was formed by the Department of Energy (DOE), under an agreement between Mr. Carl Gertz (Project Manager) and Mr. Jerry Szymanski (Physical Scientist), to review documents pertaining to Mr. Szymanski's proposal (Szymanski, 1989) that the groundwater system at Yucca Mountain is controlled by tectonic processes. Two panel members (Archambeau, Price) were chosen by Mr. Szymanski, and three members (Powers, Rudnicki, Smith) were selected by the DOE. Panel members were contracted individually for their services.

The report by Szymanski (1989) presents his view, and evidence he considers supportive, that the hydrogeologic system at and in the vicinity of Yucca Mountain is controlled by tectonic processes. He contends that these processes will eventually saturate the present-day unsaturated zone and any repository located within it. In 1987, an earlier draft version of this document was released before internal review and received considerable publicity. An internal review (Dudley and others, 1989) of this draft was released in July, 1989, after extensive interaction with Szymanski. Late in July, 1989, the current version of Szymanski's report was forwarded to the DOE. In the accompanying letter, Szymanski indicated that he had considered the extensive criticism of the draft by the internal review panel (Dudley and others, 1989), had modified and expanded certain sections, but had concluded that his concerns about the conceptual model of the hydrogeology and about site suitability were not modified. If anything, these concerns were strengthened, in Szymanski's view, during the review process. The great differences in opinion between Szymanski and the internal review panel were

therefore unresolved. Based on prior agreement with the Project Manager, Szymanski requested that an independent external review panel be named and convened to review the document and the ideas therein.

1.2 Objectives, Scope, and Focus of the Review

Three objectives of the external review have been explicitly listed (enclosure to letter, C.J. Fridrich to D.W. Powers, January 4, 1990):

1) "Review the 1989 report by J.S. Szymanski."
2) "Advise the DOE as to the technical merits (reliabilities & uncertainties) of reported data, interpretations and conclusions."
3) "Recommend tests that would help define the nature and extent of ongoing tectonic influences on groundwater conditions at Yucca Mtn."

These objectives have been addressed during the panel deliberations and through this report by the panel majority.

In a forwarding letter to the DOE accompanying his 1989 report, Szymanski requested that the review focus on two conclusions which he had derived:

'The currently available data base pertaining specifically to the Yucca Mountain groundwater system indicate (sic) that: a) the main factor which dominates and controls the hydraulic and bulk effective thermal conductivities of the local tuff "pile" is most likely the in-situ stress field; and b) the base of the Yucca Mountain groundwater system is a spacially (sic) variable "upward flux" boundary for both heat and fluid.'

and 'Reasonable but conservative interpretations of the geologic record and of the data regarding contemporary state of the in-situ stress strongly suggest that: a) the local hydraulic and bulk effective thermal conductivity structures undergo significant and cyclic changes in time scale measured in terms of tens of thousand of years; and b) the "upward flux" boundary conditions, along the base of the Yucca Mountain groundwater system, are time-dependent and are sensitive to a variety of tectonic stimulations.'

In a letter, dated Jan 4, 1990, to Dennis Powers, C.J. Fridrich concurred with the focus on the two conclusions stated above. Fridrich also stated that

"...we request that the panel consider whether the probable magnitudes and durations of the predicted phenomena can be estimated using quantitative scoping calculations, and therefore, whether the proposed events could represent a credible threat to the ability of the repository to isolate nuclear waste..." and "the Project office would like to request that the panel provide a recommendation regarding additional investigations that may be needed to resolve remaining uncertainties, as well as an evaluation of the relative priority of such investigations compared to other site characterization tests."

Fridrich noted two other points: "The review panel will have the flexibility to define the details of the review" and "DOE requests that the panel attempt to develop a consensus position whenever possible, but it is not a requirement of this review".

The panel has attempted to address these additional, more specific requests in our review. Through our deliberations, panel members individually and collectively considered the objectives of the panel. Common ground developed that the panel is principally concerned with reviewing the 1989 report by Szymanski, that the panel should develop as much consensus among members as is reasonable concerning technical issues presented by Szymanski, and that the panel should recommend further work and priorities at Yucca Mountain. Panel members developed quite divergent opinions about the overall validity of the proposals made by Szymanski and supporting arguments and evidence presented by him. We present our opinions, conclusions and recommendations as a majority report.

To understand the views of Szymanski, as well as the views of those who differ, the panel heard presentations by Szymanski and a number of scientists working on aspects of Yucca Mountain geology and hydrology. Each panel majority member made at least four field trips to Yucca Mountain and surrounding areas, and we discussed data and interpretations with many individuals. It required a concerted and intensive effort to understand the proposals made by Szymanski, both oral and written, to summarize those proposals, and to evaluate those proposals for the Yucca Mountain Project.

In the preface to the 1989 report, on page 5, Szymanski states it is "... not prudent to focus attention on evaluating whether or not I have proven the proposed conceptual understanding of the Yucca Mountain groundwater system. Rather, the efforts should be directed toward evaluating whether this understanding constitutes a good theory." The panel majority has adopted the viewpoint that our review must consider

both the theoretical foundation of Szymanski's concepts, and his attempt to validate those concepts using data from Yucca Mountain and the Nevada Test Site.

1.3 Panel History

The panel met initially in February, 1990. We met five additional times to hear presentations from various parties and to examine the merits of Szymanski's concepts. We held our last working meeting and field excursion as a full panel in December, 1990, to visit additional sites considered by Szymanski to be significant and to resolve issues on a draft report. The full panel spent many hours during these meetings debating Szymanski's concepts. At the December meeting, we decided to prepare separate majority and minority reports. As a panel, we met with the National Academy of Science panel on coupled hydrologic and tectonic processes in May, 1991, to discuss these concepts and exchange views on the evidence. Panel members writing the majority report met for the last time in July, 1991, to revisit several field sites and to finalize details of the majority report.

1.4 Acknowledgments

Many individuals, especially from the DOE and USGS, have discussed the studies at Yucca Mountain and surrounding areas, supplied data, and accompanied us to the field. Among these, Jerry Szymanski (DOE) and Gerry Frazier (SAIC) spent many hours explaining the idea of tectonic control of the hydrologic system and showing us field sites. Bill Dudley (USGS) provided insight into USGS studies completed and still underway. We appreciate the information and discussions by Dan Muhs (USGS), Zell Peterman (USGS), John Stuckless (USGS), Jack Healey (USGS), John Whitney (USGS), Emily Taylor (USGS), and Thure Cerling (Univ. Utah). Bill Sublette (SAIC) served well as our panel secretary; he helped provide documents and information, set up meetings, and he was a central point for dispersing information to our far-flung members. Carl Gertz and Dave Dobson reassured us that our panel efforts would be taken seriously by the Department of Energy.

A general chronology of the panel activities is included (Appendix B) for information.

Appendix C lists specific documents partially or entirely reviewed by the panel majority. References cited are listed at the end of the report.

2.0 PANEL SUMMARY OF SZYMANSKI'S CONCEPT

The following summary is the **panel majority's synthesis** of the key ideas presented by Szymanski in written materials, in presentations, and through extended discussions:

There are two prominent features of the geological setting in which Yucca Mountain is located: 1) the region is subject to extension by existing geological processes within the Basin and Range province, including mantle convection, and 2) deep-seated hydrothermal convection is a common occurrence in the area of Death Valley and the Nevada Test Site.

As strain accumulates in the rocks due to extension, fracture permeability increases, causing the water table to decline. Stress in the rocks closest to the ground surface eventually reaches limit equilibrium. As a result, fractures open due to shear and tensile failure, leading to substantial increases in the hydraulic conductivity of the tuffs. A surface Z is defined which separates this upper region from the underlying rock which has yet to experience significant opening. The surface Z moves downward as tectonic strain continues. Above this surface, there is spontaneous and continuing restructuring of the *in situ* stress, due to both the migration of so-called singular points [where mean normal stress is zero] and to an increasing density of such points.

Strain is broadly distributed until an earthquake leads to strain being localized (or concentrated) along larger fracture/fault zones and to decrease in the adjacent rock mass. The decrease in volume strain creates a pore pressure spike. In near-surface regions, this pressure spike causes the wall rocks to separate along larger fault and fracture zones while at greater depths, where lateral confinement is greater, the wall rock is brecciated. The rock mass between the major fracture/fault zones is compressed. Fault zones may open to widths of several meters, leading to a substantial increase in the permeability of the fault zones. The decrease in volume strain at focal depths causes rapid seismic pumping of water to and up the fault zone, possibly to the ground surface. Gases may exsolve from circulating fluids, leading to explosive conditions. The water table within the tuffs is raised because the fracture porosity is suddenly decreased.

After the strain is restructured, hydrothermal convection is enhanced along faults. Minerals precipitate in the pore space within and adjacent to the fracture zone, reducing fluid loss to the wall rock and permitting a higher rise of the convecting fluid within the fault zone. The water table may ultimately reach the ground surface, some years after the triggering earthquake. This process may continue for

hundreds or several thousands of years, until extension or other events change the conditions causing convection.

This pattern of extensional strain, strain readjustment with seismic rupture, and hydrothermal convection is cyclic. Structural domains, of the general size of Yucca Mountain, have a characteristic, but independent, tectonic strain cycle. The cycle for a structural domain is of the order of a few tens of thousands of years, and is determined by earthquake recurrence times.

Hydrologic tests indicate that, in some tuffs, the local stress conditions and fracture permeability are easily altered by fluid injection. This observation is consistent with an advanced state of extension characterizing later stages of the tectonic cycle. The large relief on the water table surface in the vicinity of Yucca Mountain is due to areas within the structural domain which are in different stages of the tectonic extension cycle.

Brecciated vein zones are prima facie evidence of the tectonic control of the hydrology. Other observable features attributed to this process are surficial and near-surface carbonate/silica deposits, occurring both in veins and on or subparallel to the present ground surface. High $^{87}Sr/^{86}Sr$ ratios and low uranium ratios in the mineral precipitates are evidence of deep circulation of fluids brought to the surface to form carbonate/silica deposits. Carbonate vein/fracture fillings in cores from Yucca Mountain and stable isotope evidence of a higher paleogeothermal gradient also attest to the circulation of upwelling fluids. The observable surface veins at Trench 14 and Busted Butte are not, however, considered to occur along the principal pathways by which the fluids to form these carbonate/silica deposits reached the surface. This conclusion is drawn because inferred ambient temperatures of formation of these deposits are low and because stable isotopes were strongly influenced by biologic processes at the surface. Other local zones, as yet undetected or unexamined, provided fluid which flowed onto the surface, producing the surficial and surface-parallel deposits as well as filling the vein deposits. Although the near-surface carbonate/silica deposits may be altered by pedogenic processes, these processes cannot account for the carbonate/silica deposits because of inadequate calcium sources, low calcium and silica solubility, and low rainfall.

The proposed repository zone, currently unsaturated, has been and will again be saturated by water driven by these processes. Resaturation is probable within a few thousand years. The site will be unlicensable in view of the evidence of these processes.

The above is a summary of the panel's understanding of the process and consequences of tectonic control of the hydrogeologic regime at Yucca Mountain as represented by Szymanski. It should be taken neither as endorsement by the panel majority nor even as a complete and current representation of Szymanski's ideas.

3.0 PANEL MAJORITY REVIEW

3.1 General Comments

Although the full panel reached initial consensus, mainly about processes key to Szymanski's concepts, the majority and minority groups decided to prepare separate reports because we differ significantly in our overall evaluation of Szymanski's concepts. The panel did not reach a consensus on the issue of whether the available data confirms the key concept in Szymanski's conceptual model, that tectonically-induced rises in the water table have saturated the tuffs in the recent geologic past and have led to discharge of groundwater at the ground surface. The panel majority also has concerns with fundamental elements of the model proposed by Szymanski to explain the linkage between the tectonic and hydrologic systems.

The report prepared by Szymanski in 1989 consists of about 220 pages of text and two volumes of references, tables, and figures. The interested reader must be prepared to dig diligently for the principal concepts, and, even then, will find that the report does not wholly represent Szymanski's current views on details of the mechanisms that link the tectonic and hydrologic systems.

The panel majority has no significant disagreement with the narrative discussion of conceptual and mathematical models of groundwater flow systems presented in Section 2 of Szymanski's report. It is a reasonable synthesis of the model-building process; and it correctly identifies the attributes of a viable conceptual model. Section 3 presents his conceptual model. The author states clearly that his intent was to provide only a conceptual framework. Little effort was devoted to quantifying the potential magnitude of the proposed effects, beyond simple order of magnitude estimates. In section 4, Szymanski attempts to validate his conceptual model through use of the Yucca Mountain and Nevada Test Site data bases.

Some of the criticism leveled at the report by scientists both inside and outside the Yucca Mountain project apparently has arisen because of the way data have been used by Szymanski to support his conceptual model. Emphasis in his report has been on the selection and interpretation of data and processes in a way that supports his concepts, relying often on assertion that "conventional" ideas are incorrect or inadequate to describe the hydrogeological system at Yucca Mountain. Indeed, there is no reason to expect the current hydrogeological understanding of Yucca Mountain to be correct in all its details. We have the sense that Szymanski at times too readily accepts data in

support of his concept, without critical evaluation, and too quickly rejects alternative explanations in keeping with conventional hydrological interpretations. In other instances, he acknowledges the possibility of alternative interpretations of the data, given the uncertainty in the data base. There are at least several instances where the statement is made that if one aspect of his conceptual model is not validated, this is not a concern if some other (unspecified) process will have the same effect (e.g., p. 3-11, 3-25; Szymanski, 1989). The panel majority disagrees with this viewpoint on philosophical grounds, and it is inconsistent with Szymanski's own description of good modeling practice.

Principal concerns of this review are whether the conceptual foundation is established and whether the data are sufficiently supportive to require further investigations specific to his concepts. Our review comments are broadly arranged from more general comments about the documents, objectives, and concepts, to some statements about processes, to more specific views and discussion of the investigations and available data from Yucca Mountain. We recommend additional studies and summary reports in the concluding section of our report.

3.2 Overall Purpose of Report by Szymanski

The stated purpose of the document (Szymanski, 1989) is to be provocative and ' "to provoke initiation of an understanding on a qualitative or conceptual basis," of the groundwater system operating in the area of Yucca Mountain.' There is no doubt that the document succeeded in being provocative. At this time, it is difficult to judge whether the report itself has positively provoked such understanding. For example, much time and scientific effort have been expended on surficial deposits considered by Szymanski as definitive evidence of tectonic control of the hydrologic system. Szymanski believes that routine field observations and the data gathered to date unequivocally demonstrate that these deposits were derived from upwelling fluids. Project investigators responsible for field and laboratory studies rather uniformly interpret the origin of these deposits in terms of surficial processes. Data have been acquired to address the origin of these deposits, but the certainty of the interpretations held by various parties has not changed. This lack of resolution occurs, in part, because Szymanski did not cast his concept (of upwelling fluids forming these deposits) as an hypothesis with testable consequences, despite the listing of issues said to be important for testing. Additional data gathering and

interpretation were provoked, but no criteria were provided to judge the results against a concept of upwelling fluids. Furthermore, we believe that the provocative tone of the report and ensuing discussions has focused attention on surficial deposits to the detriment of other important project studies such as detailed investigation of fracture fillings in cores from Yucca Mountain.

Another objective stated by Szymanski is that the document should serve as a "management tool." From our observations, the report and discussions by Szymanski appear to have stimulated further work, though it is not apparent that either the report or the discussions served to "manage" the studies. The report is devoted to the single issue perceived by Szymanski to override all other concerns for Yucca Mountain. In focusing attention on this issue, the document has perhaps served the author's intended "management" function. Nevertheless, the features of the report mentioned above make it ill-suited for the purpose of directing relevant site investigations.

The report has served an important function as an attempt to summarize a range of information bearing on a subject. It is important that information about a variety of site suitability issues be synthesized, though a more objective (balanced) approach and more succinct style would have been helpful.

In a draft document, dated May 15, 1990, and prepared for the panel, Szymanski discussed and interpreted a variety of geochemical data. Although this document is discussed only briefly in this report, the draft by Szymanski was considered by the entire panel, and extensive comments by one member of the panel majority were forwarded to Szymanski. The document was intended to show how the range of geochemical data support his ideas and contradict the view of a pedogenic origin of the carbonate/silica deposits. The report was valuable in demonstrating his view of the geochemical data, though the panel majority was not convinced by his interpretations.

To close this subsection, the panel majority draws the reader's attention to an important difference of opinion between us and Szymanski. We believe he overstates the case that the available data base for the Nevada Test Site is one of truly extraordinary proportions (Szymanski, 1989; p. 4-5). While the data base is large, we believe that some of the data are not applicable to this problem, some are of uncertain reliability, and data regarding several key issues have not yet been collected. For example, hydrologic data from wells completed below the water table must be interpreted with caution. Completion intervals commonly exceed many tens of meters; in numerous cases, they exceed one hundred meters. These long completion intervals introduce

substantial uncertainty in estimates of hydraulic potential, in derived estimates of hydraulic conductivity, and in the interpretation of chemical data. Much of the temperature data is obtained in open boreholes, not intended for dedicated heat flow measurements. Age dates for vein filling carbonates in the unsaturated zone at Yucca Mountain may be subject to considerable error, or the dates do not constrain the timing of events. Strain measurements at Yucca Mountain have not yet been obtained. The present data base is not adequate to quantify with certainty the extent to which the tectonic setting of Yucca Mountain may perturb the regional, topographically-driven groundwater flow system.

3.3 Key Processes

To comprehend the many processes and linkages between processes, the full panel found it helpful to summarize the key components of Szymanski's conceptual model. The summaries presented here are based on seven key processes. For each process, the panel identified the consequences of the process (that is, why the process is included in the model) and the evidence offered in support of the process occurring in and around the region at Yucca Mountain. Both the statement of consequences and the evidence offered in support of the processes reflect Szymanski's viewpoint, and are not necessarily those of either the panel majority or minority.

In panel discussions, Szymanski was presented with the panel's synthesis of his model, and he concurred that it was a reasonable synthesis. Consequences and evidence not included in the panel's original synthesis were added if the author felt important points had been omitted. New evidence not included in the 1989 report, but which Szymanski feels supports his model, is included in the synthesis and is so identified.

The seven key processes are:

1) mantle convection;
2) cyclic variation in the *in situ* stress field;
3) tectonic deformation model Z(x,y,t), and its influence on the field-scale hydraulic properties of the tuffs;
4) episodic wall rock separation of large magnitude;
5) dilatant zones at focal depths - seismic pumping;
6) vein and calcrete formation by upwelling fluids, including mixing with young meteoric water;
7) transient hydrothermal convection.

Processes two through six are closely related, and represent a finer subdivision of Szymanski's concept than do processes one and seven. The cyclic variation in process 2 refers to the sequence of processes that develop through time and are re-initiated following a major earthquake. Cyclicity does not imply periodicity.

Process 1. Mantle Convection

Consequence:

i) Basal shear to drive cyclic deformation above the surface Z.

ii) Delivery of heat to the upper crust, with high lateral thermal gradients, to drive hydrothermal convection.

Evidence presented in support of mantle convection:

- A seismic velocity anomaly is present in the upper mantle beneath Yucca Mountain, suggesting a partially molten upper mantle.
- The scale of inhomogeneity in P wave seismic velocity reflects heterogeneous viscosity, demonstrating the high lateral thermal gradient.
- Nearby volcanic cones have a basaltic composition.

Process 2. Cyclic Variation in the In Situ Stress Field

Consequence:

i) The rock mass at Yucca Mountain must be characterized in terms of the cyclic deformation of a fractured medium, containing both isotropic and singular points. Fractures are pervasive. Fractures will dilate if they are appropriately oriented to the current, local stress field.

ii) Deformation is cyclic because of faulting. Deformation is variable in space because of local stress domains, each associated with slip on a dominant fault and having a characteristic length of the order of 5 - 10 km. Different stress domains of this length scale are distinguished on the basis of their position in the time cycle. Duration of the cycle is of the order of 10^4 years.

Evidence presented in support of cyclic variation in the stress field:

- The state of stress across Yucca Mountain, and comparisons to other areas on the Nevada Test Site.
- Inferences on the state of stress from hydraulic tests, and its spatial correlation with the water table configuration.

- Deformational history of Pleistocene movements on faults.
- Vein-filling breccias provide an estimate of extension in the region of Yucca Mountain; 250 m in 10^7 years, 10 m in 250 ka (the latter estimate using veins in alluvium).

Process 3. Tectonic Deformation Model Z(x,y,t), and Its Influence on Field Scale Hydraulic Properties of Tuffs

Consequence:

i) The groundwater flow system in the tuffs is controlled by the tectonic setting of Yucca Mountain.

ii) The water table is not a durable characteristic of the flow system.

iii) The state of stress in a deforming fractured medium, not the lithostratigraphic framework, controls the hydraulic properties of the altered tuffs in the zone below the water table.

Evidence present in support of the tectonic deformation model, together with the hydrologic implications:

- The present-day water table configuration and its correlation with limited *in situ* stress measurements.
- Correlation between gradients in hydraulic conductivity and gradients in the *in situ* stress at Rainier Mesa/Yucca Flat and at Yucca Mountain.
- The large magnitude of the gradient in hydraulic conductivity in single boreholes.
- The character of the fluid pressure distribution with depth (division into zones I, II, and III), and temporal variations in water levels in the limited data record that is available.

Process 4. Episodic Wall Rock Separation of Large Magnitude

Consequence:

i) Episodic wall rock separation resets the *in situ* stress field, with the surface Z(x,y,t) returning to a position close to the ground surface, to begin

another tectonic cycle. Thus, limit equilibrium conditions only occur close to the ground surface at the beginning of a new tectonic cycle.

ii) Formation of wall rock separations on fissures, and the formation of breccias at greater depths.

iii) A change in thermal conditions to enhance hydrothermal convection.

Evidence presented in support of episodic wall rock separation:

- Field observation (Devil's Hole, the site 5 mi east of Lathrop Wells on Highway 95, along Bare Mountain and Solitario Canyon Faults).
- Measurements of stress at Yucca Mountain.
- Massive appearance of calcite veining, suggesting single rather than multiple events.

Process 5. Dilatant Zones at Focal Depths - Seismic Pumping

Consequence:

i) A source of pressure work to create wall rock separation.

ii) A source of fluid to the fault zone.

These two consequences are stated in the 1989 report. In discussions with the full panel, Szymanski indicated that seismic pumping from a dilatant zone at focal depths is not an essential part of his conceptual model; other processes could trigger the readjustment of the stress field. Szymanski emphasized that the key issue is that the critical value of closure pressure approaches zero above the surface Z. However, Szymanski is absolutely certain on the basis of field evidence that seismic pumping has occurred at Yucca Mountain. Seismic pumping does not necessarily contribute to vein formation.

Evidence presented in support of seismic pumping from focal depths:

- By analogy to groundwater discharges related to seismic events in other tectonically active settings.
- Field evidence, that is wall rock separations and some breccias, indicates a pressure pulse at some time in the past.
- The overall tectonic setting of Yucca Mountain favors seismic pumping.

Process 6. Vein and Calcrete Formation by Upwelling Fluids, Including Mixing with Young Meteoric Waters

Consequences:

i) The veins and calcretes provide the most direct evidence for upwelling of fluids from depth, indicating the water table has reached the land surface in the past.

ii) Resealing of fracture hydraulic conductivity near zones of upwelling ("gluing").

iii) Increase in the geothermal gradient because of upward-welling fluids and reduction in the effective thermal conductivity of the tuffs. The rise in the water table must be accompanied by a rise in subsurface temperatures.

Evidence presented in support of vein and calcrete formation by upwelling fluids:

- Surface textures, banding, frequency of veining, morphology and structural relationships within veins and between the veins and calcretes.
- Elimination of other possible origins (i.e. rainfall, solution of calcite originating from dustfall, followed by surface and/or shallow subsurface flow).
- Isotopic characteristics and precipitation temperature of deposits classified as travertines by Szabo and Kyser (1984).

Szymanski has suggested additional evidence that does not appear in the 1989 report:

- Inferred rapid precipitation rates of minerals.
- Uranium series geochemistry (low and heterogeneous values of the $^{234}U/^{238}U$ ratios).
- Correlation of oxygen/carbon ratios with those in the Amargosa Basin.
- Depthward gradient in $\delta\ ^{18}O$ and $\delta\ ^{13}C$, implying a geothermal gradient greater than $22^{o}C/km$, the estimated value for the present-day thermal regime.

Process 7. Transient Hydrothermal Convection

Consequence:

i) Formation of water table mounds and sinks. Above an upwelling limb of a convection cell, the water table may reach the ground surface.

ii) Delivery of calcium and silica to the land surface to produce veins and calcretes which incorporate uranium from depth.

iii) Healing of the rock mass adjacent to the fault zone by cementation, for a distance on the order of 1 km from the fault.

iv) Cyclic discharge of groundwater at the surface, with a chemical signature that reflects some proportion of water having circulated to depths of at least several kilometers.

v) Large input of heat resulting in a temperature increase in the upper crust, beginning after seismic rupture, and lasting on a time scale of order 10^3 years.

<u>Evidence presented in support of transient hydrothermal convection:</u>

- Occurrence of spring deposits at elevations far above the present water table.
- The isotopic signatures and age dates of spring deposits.
- The present-day geothermal gradient, compared to paleotemperatures inferred from precipitation temperatures of calcites.
- Expected Rayleigh numbers exceed critical Rayleigh numbers for the onset of convection (calculated for an assumed geometry, permeability, and geothermal gradient).
- The presence of large lateral temperature gradients at and immediately below the water table.
- Laterally-homogeneous heat input from the mantle.
- Identification of water table mounds at several sites within the Nevada Test Site.

4.0 PANEL MAJORITY POSITIONS

4.1 Preamble

After lengthy discussion, the full panel did not reach a consensus on the issue of whether the available data confirms, requires, or even supports the essential concept underlying Szymanski's model: that tectonically-induced rises in the water table have repeatedly saturated the tuffs and discharged groundwater at the land surface during the recent geologic past. Some of the initial positions discussed and prepared by the full panel that related to our discussion of key processes (section 3) have since been modified and are included here as majority opinions. More detailed discussion that led to these positions is presented in section 5 of this report.

4.2 Summary Positions

1. Geological conditions within the Basin and Range are unusual, on a global scale, and are highly heterogeneous. The unusual conditions include magnitude and rates of extension, heat flow, and large and localized lateral changes in the mantle/lower crust as indicated by seismic velocity properties.

2. The key features of the tectonic setting at Yucca Mountain that have a potential influence on the hydrologic system are the following: Yucca Mountain is located in an extensional terrain, in a region with high heat flux, and in an area with nearby evidence of geologically young volcanic activity, indicating upwelling mantle material. Inferences on mantle convection as a cause of extension are not a critical aspect of Szymanski's model.

3. It is unclear to what extent Yucca Mountain is representative, unusual, or unique within the Basin and Range. The Yucca Mountain area has been considered by Szymanski to be at least unusual, if not unique, based on his interpretation of the origin of the carbonate/silica deposits in the area. We do not see compelling evidence, however, that Yucca Mountain is unusual within its regional tectonic setting. As an example, the extension rate inferred from the cumulative extension estimated by Szymanski does not appear to be unusual with respect to other areas within the Basin and Range.

4. Key differences between what Szymanski refers to as a "simple hydrogeologic model", and the model he proposes are the following: 1) the spatial and temporal dependence in the hydraulic properties of the tuffs, originating from the evolution of the *in situ* stress field; 2) pressure transients generated as a consequence of strain readjustments following seismic rupture; and 3) recurrent, deep-seated hydrothermal convection within the through-going faults of the area. Szymanski is correct in isolating these issues as important ones to be considered when characterizing large-scale groundwater flow at Yucca Mountain. Each issue represents a concern that requires careful evaluation before it is either accepted or rejected as a basis for analyzing the hydrogeologic system.

5. Because the average minimum horizontal stress is low at Yucca Mountain, as inferred from hydraulic fracturing tests, it is likely that some fractures will have open segments. On these segments, the minimum principal stress will be zero, but at contact points the compressive stresses will be much higher. The presence of open fracture segments implies that stress is heterogeneous on a size scale perhaps as large as 10 m and certainly on a smaller size scale. Open fracture segments may change aperture with small changes in stress or pore pressure. Laboratory and *in situ* testing of rough fractures that contain open segments indicates, however, that the normal stiffness is high even at low normal stresses. Hence, the presence of open segments of fractures will not dominate the mechanical response of the rock mass.

6. Structural domains, of the scale of Yucca Mountain and having a common strain history controlled by a major fault, are proposed to explain the tectonic and hydrogeologic history of Yucca Mountain. The existence of structural domains of this size is neither demonstrated nor rejected by the data available. While the concept of strain domains (of the order of 10 to 100 km^2) is useful in summarizing the Szymanski model, it is difficult, if not impossible, to locate their boundaries in a practical sense.

7. Because of the extensional tectonic setting, existing and new fractures are opening within the tuffs during the period prior to earthquake rupture. Fractures with open segments will probably be more frequent in the welded tuffs than in the nonwelded tuff units.

8. According to Szymanski, a surface (Z) divides a near-surface region in which localized shear failure on fractures, accompanied by opening of fractures, has occurred, from a deeper region in which shear failure has not occurred during the interseismic period. Above the Z surface, heterogeneous stress due to open fractures is expected; below this surface, the magnitudes of these stress variations would be greatly diminished. Thus, the spatial variation of the contemporary Z surface could conceivably be inferred from careful stress measurements with depth, but lithologic factors may make interpretations ambiguous. The concept of a Z surface seems useful to describe qualitatively what is happening during extension or during the interseismic period, as proposed by Szymanski. It will not be easy to determine the position of this surface in the field, and establishing contemporary changes in the position of the Z surface seems impossible.

9. The concept of recurrence intervals for earthquakes is similar to Szymanski's proposal that earthquakes will be "cyclical" in the Yucca Mountain area. Repeated earthquakes may be expected on major faults around Yucca Mountain. Both physical and radiometric evidence are consistent with multiple movements along some faults. Dating of fault deposits indicates repeated episodes. Szymanski's proposal concerning the scale of strain reorganization associated with seismic rupture rests on features, such as the surficial carbonate/silica deposits, that, through a sequences of inferences, imply to him large scale readjustment.

10. Hydraulic fracturing tests suggest that at Yucca Mountain areas of lower principal stresses correlate with a lower water table while areas with higher principal stresses correlate with a higher water table. It is not possible to conclude on this evidence that portions of the structural domain at Yucca Mountain are at differing stages in the proposed tectonic cycle.

11. Szymanski has adopted the dilatancy-diffusion model, with the formation of a dilatant zone at focal depths, as representative of the earthquake nucleation process. Although this model cannot be dismissed entirely, most geophysicists believe there is no credible evidence of this process.

12. Seismic pumping from dilatant zones at focal depths is not required to reset the strain field; an earthquake, even unaccompanied by seismic pumping, could do this, although not necessarily in the manner assumed by Szymanski. Seismic pumping could contribute to the discharge of fluid, but generous estimates suggest that the volume of fluid discharge is too small to saturate the unsaturated zone. Futhermore, we believe this mechanism to be unlikely in an extensional regime.

13. Although Szymanski considers large wall rock separations to be an essential element of his model, wall rock separations are not required to relieve strain in the rocks surrounding the fault on which slip occurs. Near-surface openings could result from the kinematics of slip on listric faults, although there is no seismological or geodetic evidence of substantial openings at depth. We consider it unlikely that large wall rock separations (on the order of tens of centimeters to several meters) are the result of a single movement as proposed by Szymanski. Should a fault open suddenly at depth, the opening is likely to decrease pore pressure at the fault. Compression of the wall rock accompanying the opening would increase the pore pressure in the wall rock. Increased pore pressures could open veins and joints in the vicinity of the fault. Breccias could be formed by implosion toward the fracture zone. Hence, the presence of breccias need not indicate a large pressure increase within the fault zone as proposed by Szymanski.

14. Although strain will be reorganized at the time of seismic rupture, the magnitude and extent of the effect on permeability and fluid pressure claimed by Szymanski have not been demonstrated. Many fractures will close by strain relief associated with earthquakes. The pattern of strain relief will be complicated and some fractures will be opening or created while others are closing. Calculations presented by Szymanski (1989) are inadequate to support his claim about the magnitude of the effects.

15. Szymanski concludes that the main factor which dominates the hydraulic conductivity of the tuffs is the *in situ* stress. There is no convincing evidence, however, to support his claim that the lithostratigraphic framework can be relegated to a role of minor or no importance in influencing rates and patterns of groundwater flow or when interpreting field data.

16. Closure of fractures that accompanies seismic rupture will decrease the bulk hydraulic conductivity of the tuffs. Because the pattern of strain alteration will be complex and hydraulic conductivity is not related to fracture geometry in a simple way, the magnitude of the effect on hydraulic conductivity is uncertain. Observations from other earthquakes suggest that in some instances the effects on hydraulic conductivity could be large, but these have been primarily increases in near-surface regions. While observations are reported in the literature of the effects of seismic rupture on groundwater flow systems, large and durable increases in the water table elevation have not been observed.

17. Hydrogeological criteria presented by Szymanski in support of his conceptual model do not provide a unique basis for distinguishing the effects of the tectonic setting on subsurface fluid flow. "Conventional" hydrogeological interpretations cannot be rejected in explaining the present hydrologic data base.

18. Isotopic characteristics of the surficial carbonate and silica deposits, including the fractionation between calcite and occluded organic carbon, are consistent with a pedogenic origin. The panel sees no reason to reject surficial sources of calcite and silica to account for these deposits. The spectrum of ages and physical relationships for some deposits indicate differing episodes of mineral formation, not single massive events, though other deposits are undated or have only a single date. The known groundwater sources under Yucca Mountain yield samples that differ chemically and isotopically from the fluids necessary to produce the surficial carbonate/silica deposits.

19. The panel agrees with Szymanski's statements during discussions with the full panel that the Trench 14 deposits are not on the upwelling source of fluids. In order for Szymanski's model to account for the Trench 14 deposits, the fluid source would have to be upslope of the existing trench and deposits. A source of upwelling fluid should show both a thermal anomaly and stable isotope characteristics not affected by biogenic activity.

20. Vein-filling deposits at depth remain an open question, given fewer available data collected from a time when enquiry was less pointed. The carbonate observed to be filling veins throughout the unsaturated zone is an important feature of the Yucca Mountain site. The origin and mode of deposition of these deposits is an issue that must be resolved with a high degree of certainty. Hydrologic conditions leading to the formation of the deeper vein-filling carbonates, should they originate from infiltration of meteoric water, are not well understood. Recurrence intervals, should the conditions leading to vein formation be episodic, are not constrained by the existing data base.

21. The panel majority views the ideas presented by Szymanski about the geochemistry associated with tectonic processes as so broadly drawn that any result will fit. Pathways are permitted that allow thermal loads to be dissipated and geochemical signatures to be overwhelmed by either surficial processes or shallow meteoric water. From this perspective, his conceptual model cannot be rejected on the basis of geochemical data.

22. Hydrothermal convection is a potential mechanism for changing fluid fluxes within the saturated zone and affecting, to an undetermined degree, the unsaturated zone. The regional heat flux and nearby volcanic activity suggest the region around Yucca Mountain is favorable for hydrothermal convection. If a low velocity zone exists in the crust beneath Yucca Mountain, indicating partial melting, or volcanic activity was renewed near Yucca Mountain, such as at Crater Flat, hydrothermal convection in the vicinity of Yucca Mountain would be highly probable. The possibility that convective circulation may be initiated by renewed volcanism, and the consequences of such a component of flow on the suitability of Yucca Mountain to host a repository must be addressed.

23. There is no confirmed mineral evidence of enhanced fluid temperatures in the geologically recent past at Yucca Mountain. A small subset of isotopic data from core below the water table of one hole suggests for that hole that paleogeothermal gradients more than 400,000 years ago were higher than present temperature gradients in that hole. The panel majority does not interpret any known data to indicate that, in the

recent geologic history of the area, hydrothermal circulation brought any fluids to the surface at temperatures significantly different from ambient conditions.

24. The critical issue in the debate about the origin of the vein deposits in the unsaturated zone is what these deposits may indicate about the potential for saturation of the present-day vadose zone. Past investigations have focussed too narrowly on competing ideas about the source of the fluids that transported and deposited the calcite and silica. An integrated summary of the paleohydrogeologic history of the unsaturated zone at and in the vicinity of Yucca Mountain is essential.

25. There is little theoretical support to expect the hydrologic system at Yucca Mountain to evolve in the manner predicted by Szymanski (1989). Certain elements of the concept are appropriate. However, some key assumptions are either overly restrictive, or the processes are viewed in too simple a manner to be representative of actual conditions. Because Szymanski did not cast his conceptual model in the form of testable hypotheses, he assumes undue flexibility in interpreting field data as supportive evidence for his conceptual model. The current data do not support the conclusion that the effects of the tectonic system on hydrologic processes are as large as Szymanski claims. In addition, the current data are not adequate to confirm that recurrence intervals lie within the time frame of concern in assessing site suitability to host a nuclear waste repository.

26. There are issues related to the tectonic influence on Yucca Mountain hydrologic systems that merit further and pointed investigations. Studies to refine the paleohydrogeologic history of the present-day unsaturated zone, cast in the form of testable hypotheses, should not be delayed. The specific proposals made by Szymanski need not, however, receive any special consideration during site characterization.

5.0 REVIEW OF INFORMATION KEY TO CONCEPTS

5.1 Introduction

Szymanski has assembled a variety of data, observations, and personal interpretations of information to support his ideas. From his main document (Szymanski, 1989), we see that the general tectonic setting, specific field observations about faults and carbonate/silica deposits, and hydrologic observations are the main factors in developing and supporting his ideas. In a later, less widely distributed document, Szymanski (1990) interpreted various geochemical data as supporting the concept of upwelling fluids as a source for the carbonate/silica deposits and as rejecting an origin tied to surficial sources and processes. These documents provide the framework for our review of the information which is key to the ideas proposed by Szymanski.

We also include a limited amount of information and ideas which Szymanski presented to the panel orally and which we believe represents an important view he holds. To be sure, we know that some of his ideas have changed in their detail; we have not attempted to keep pace with his most recent thinking. For example, the panel received from Szymanski copies of illustrations accompanying his presentation to a Penrose conference in February, 1991, and attachments to a letter he sent to Science magazine in response to a paper by Quade and Cerling (1990). The panel majority is not explicitly reviewing and commenting on these materials; they are inadequate as a written record of ideas, data sources, and interpretation to formally review. Nevertheless, it has been helpful to the panel to have received this material and to incorporate the ideas Szymanski has expressed within the general framework of our review.

Within this section, we examine model concepts, observations, data, and interpretations which are relevant to assess the ideas he has presented. For convenience, we have organized this section by broad subject area, covering the conceptual model, geological, geochemical, and then hydrological information.

5.2 The Conceptual Model

The conceptual model Szymanski has proposed to explain tectonic control of the hydrologic system is described in detail in section 3 of his 1989 report. The key

features of this model, as stated by Szymanski and noted earlier in the introduction to this report, are restated here:

1) The main factor which dominates and controls the hydraulic and thermal conductivities of the tuffs at Yucca Mountain is the *in situ* stress field. The hydraulic and thermal properties of the tuffs undergo significant and cyclic changes on a time scale on the order of 10^4 years.

2) The base of the Yucca Mountain groundwater system is a spatially variable, upward flux boundary for both heat and fluid. The upward flux boundary conditions are time dependent and sensitive to tectonic stimulations.

3) As a consequence of processes 1) and 2), the groundwater flow system evolves through time in a cyclic pattern directly related to the tectonic setting in which Yucca Mountain is located. Of special significance to the Yucca Mountain Project is Szymanski's conclusion that the present-day unsaturated zone has been subject to repeated saturation in the geologically-recent past, including the discharge of upwelling fluids at the ground surface.

This section of the report presents the majority view on certain key aspects of this conceptual model. For brevity, we adopt the same nomenclature as Szymanski, referring to the overall concept as one describing a "deforming fractured medium." The focus in this subsection is on a discussion of the theoretical foundations of the model; subsequent subsections deal with Szymanski's attempt to support the conceptual model on the basis of observational data. For clarity, we have organized our comments on the conceptual model in two parts. First, we discuss the issues of primary concern; following that we flag some issues of secondary importance.

The panel majority has concluded that there is little theoretical support to expect that the hydrogeologic system at Yucca Mountain evolves in the manner predicted by Szymanski (1989). Certain elements of the model are appropriate. However, some key assumptions made by Szymanski are overly restrictive or the processes are viewed in too simple a manner to represent actual conditions. For example, the mechanism of strain readjustment is simplistic, and the estimated magnitude of the influence of strain readjustment on subsurface fluid pressures is poorly constrained. These conclusions relate specifically to the conceptual model proposed by Szymanski; the reader is cautioned not to infer from this statement that the panel is of the opinion that the tectonic setting has no influence on groundwater flow at Yucca Mountain. Furthermore,

it is our opinion that a high degree of confidence will be necessary in the assessment of the hydrologic effects of certain post-closure tectonic processes.

5.2.1 Issues of Primary Importance

In this subsection we provide comments and discuss our concerns about a number of key aspects of Szymanski's conceptual model. These issues are as follows: 1) a model framework to analyze groundwater flow, 2) continuum approximations, 3) pressure-depth relationships, 4) water table gradients and a water table rise, 5) recognition of a deforming fractured medium, 6) thermal models, 7) effective thermal conductivity, 8) basal boundary conditions, 9) calculation of a water table rise due to thermal effects, and 10) earthquake processes.

A Model Framework to Analyze Groundwater Flow. In section 1.0 of Szymanski (1989), the author expresses concern that only a "simple" model of groundwater flow has been adopted in developing the Site Characterization Plan for Yucca Mountain. This simple model corresponds to that used, for example, in a hydrogeologic investigation of a shallow aquifer system. In his view, a simple groundwater model has the following properties: 1) the water table configuration controls the three-dimensional distribution of hydraulic head within the saturated zone beneath and around Yucca Mountain, 2) the thermal regime is unimportant in influencing patterns and rates of groundwater flow, and buoyancy forces can be neglected, 3) surface recharge and discharge across the water table adequately characterizes fluid input/output to the flow system, 4) the boundary condition at the base of the model is not of importance in determining the nature of the flow patterns, 5) within the vadose zone of a recharge area, fluid moves downward by gravity flow, and 6) the medium is nondeformable, and therefore, permeability and storativity are time invariant.

These assumptions are commonly invoked in groundwater investigations of shallow subsurface flow. In that instance, they are frequently found to be reasonable approximations. Szymanski is correct in questioning these assumptions when characterizing large-scale flow in a geologic setting such as that found at Yucca Mountain. Each assumption requires careful evaluation before being accepted or rejected as a basis for analysis of the hydrogeologic system. As an aside, we note that, in what Szymanski terms a simple groundwater model, it is the combined effect of

the water table configuration and the lithostratigraphy that controls the three-dimensional distribution of hydraulic head, not the water table configuration alone, as listed in 1) above.

The essential differences between the so-called simple groundwater model and the framework proposed by Szymanski are as follows: 1) the temporal and spatial dependence in the hydraulic properties of the tuffs, originating from the evolution of the *in situ* stress field; 2) pressure transients generated as a consequence of strain readjustments following seismic rupture; and 3) recurrent, deep-seated hydrothermal convection within the through-going faults of the area. The assumptions that Szymanski identifies with a simple groundwater model are not strictly applicable to a tectonic setting such as that in the vicinity of Yucca Mountain. We agree it is appropriate to consider the potential effects of the three issues just listed, and that more complex simulation models may be needed to quantify their effects. In developing a model framework for the Yucca Mountain system, it is important to recognize that there is uncertainty in the extent to which the large-scale hydraulic properties of a rock mass may vary through geologic time in an area undergoing tectonic extension. There is a paucity of data to suggest the magnitude of permeability variations and porosity reduction that may be triggered by seismic rupture and release of strain. Considerable uncertainty exists in trying to formulate hydrogeologic models that would take these processes into account on a site-specific basis. We see no firm evidence, however, that the magnitude of these effects are as large as claimed by Szymanski.

Continuum Approximations. Central to Szymanski's conceptual model is the idea of a "deforming fractured medium." He does not define this term precisely, but the main idea is illustrated by Plates 3.3.2.2-5,-6 (Szymanski, 1989): Relatively stiff (and impermeable) blocks of matrix material are separated by relatively compliant fractures that provide channels for fluid flow. This illustration also makes clear the role that this idea plays in Szymanski's conjectures: If the strain changes caused by tectonic processes are accomodated primarily by changes in aperture of fractures, then the effects on the hydrogeologic system will be much more dramatic than if they are accomodated primarily by deformation of the (fractured) matrix material.

In assessing the validity of this approximation from both a mechanical and hydrogeologic perspective, the questions of scale and of relative stiffness are critical. If the length scale of interest is much greater than the average spacing

between fractures, the rock mass can be treated effectively as a continuous medium with the effects of the fractures included as a reduction in the stiffness of the rock mass (perhaps, in a nonlinear fashion, dependent on overall strain) and an increase in its permeability. Conversely, if the length scale of interest is less than, or even about the same as, the average spacing between fractures, then the fractures must be treated as discrete features. In some intermediate range, neither of these idealizations would be appropriate. In addition, if the modulus of the rock (between the fractures) is much less than the fracture stiffness multiplied by the average spacing between the fractures, the fractures contribute negligibly to the deformation. Szymanski ignores this issue of scale, preferring to simply assert the importance of treating Yucca Mountain as a "deforming fractured medium" and interpreting observations in terms of this assumption.

The panel finds no basis for the idealization of a deforming fractured medium adopted by Szymanski. Laboratory and *in situ* testing of joints indicates that they are extremely stiff even at the lowest normal effective stress levels measured at Yucca Mountain (3.5 MPa in USW G-1; Stock and others, 1985). For example, laboratory tests by Olsson (1987) on the Topopah Spring Tuff indicate that above an effective normal stress of 2 MPa, mated joints are essentially closed (mechanically) and the normal stiffness of unmated joints is large. Although these results were obtained from laboratory size specimens, an unmated fracture is likely to be at least as rough as a typical fracture in the field. The stiffness value is consistent with that inferred by Walsh and Grossenbaugh (1979) from data obtained by Pratt and others (1977) from *in situ* testing of a jointed granite. This observation means that relatively little of the deformation is accomodated by the larger fractures.

It is also essential to distinguish between the hydraulic properties of a single fracture and those for a representative volume of the rock mass. Szymanski presents relationships for single fractures and then implicitly adopts the same relationships to describe large-scale behavior. This approach is used by Szymanski to estimate the effects of strain on both hydraulic conductivity and storativity.

For a single fracture represented as a smooth parallel plate, the equivalent hydraulic conductivity is

$$K_f = cb^2$$

where b is fracture aperture and c is a constant of proportionality. If the fracture dilates by a factor of 100, then the hydraulic conductivity of the fracture increases

by a factor of 10^4. From this calculation, Szymanski infers that locally, above the Z surface, the rock mass hydraulic conductivity could increase by a factor of 10^4. For this inference to be correct, all the fractures forming connected flow paths would have to dilate by the same factor. However, the hydraulic conductivity of a fractured rock mass depends upon fracture density, connectivity, and aperture in a complex manner. All fractures do not contribute equally to rock mass permeability. Not all fractures will be favorably oriented with respect to the stress field to promote dilation. Extrapolation to a 10^4 increase in rock mass permeability is very difficult to defend on this basis. While it is possible to argue that this relationship represents an upper bound, it is not clear what a representative value for the increase in rock mass permeability may be.

Szymanski assumes that the storativity of a single fracture is equal to the value of the conducting aperture. From this assumption, he approximates the change in storativity by the square root of the change in hydraulic conductivity. On this basis he concludes that above the surface Z, large volumes of water are held in temporary storage (this follows because a 10^4 increase in hydraulic conductivity gives a 10^2 increase in storativity). Again, no regard is given to the scale at which these approximations can be applied.

The more relevant parameter to consider is the storativity of a representative volume of the rock mass, and not an individual fracture. Under confined conditions, the storativity is the sum of two components: 1) the elastic compressibility of the medium, and 2) the compressibility of water. For a representative volume of saturated tuff, the storativity depends upon the elastic compressibility of the rock mass, at a given value of the effective normal stress. Changes in storativity are properly related to how shear displacement and tensile opening modify the elastic properties of a dilated rock mass, rather than equating storativity to the incremental volume of open fractures. Although some laboratory measurements of these changes are available, it is not clear how they could be scaled up to the field problem.

Pressure-Depth Relationships. In section 3.4.4 of Szymanski (1989), it is stated that in an advanced stage of deformation, it should be possible to recognize three zones in the depthward distribution of hydraulic potential. This zonation reflects the transient readjustment of pressures to a decline in the water table as the rock mass above Z(x,y,t) dilates with increasing tectonic extension. The zones are as follows:

Zone I - fluid pressures are hydrostatic and, locally, the effective stress is equal to the closure pressure.

Zone II - values of hydraulic potential are depth-dependent.

Zone III - values of fluid pressure remain at their initial pressure distribution, corresponding to a water table elevation that is observed at the beginning of a new tectonic cycle.

Zone I is described as a region where fluid pressures have equilibrated to a new water table position, while zone II is the region where transient readjustment is currently underway. Zone III is identified by the region where fluid pressure changes due to the falling water table have yet to penetrate to any significant extent.

The magnitude of the difference between the fluid pressure at the top of zone III, and the pressure that would be observed there under hydrostatic conditions in equilibrium with the water table elevation, is referred to by Szymanski as an overpressure. The panel views the choice of the term "overpressure" as inappropriate, though technically correct. The term overpressure is conventionally used to indicate the development of excess pressure in compacting sedimentary basins or regions of tectonic compression, where lithostatic pressure gradients develop and pressures may exceed hydrostatic pressure by 30 or 40 MPa. The pressure in zone III is more properly characterized as a zone that is in disequilibrium with the present-day water table elevation, with disequilibrium pressures, should they develop, on the order of several MPa.

Several points are of concern to the panel. First, fluid pressure in zone I will not be precisely hydrostatic: fluid pressures there will vary with depth to the extent that there is an active topographically driven flow system within the rock mass. Second, vertical gradients in hydraulic head are an expected consequence of steady state, three dimensional groundwater flow in a nondeforming, heterogeneous medium. The magnitude of any "overpressure" related to a declining water table is likely to be similar to, or smaller than, that related to lithostratigraphic effects. The vertical zonation in hydraulic potential conceived by Szymanski is not diagnostic of a deforming fractured medium.

Szymanski (1989) anticipates a vertical zonation in the hydraulic potential on the grounds that a pressure disequilibrium will develop between the falling water table, and the fluid pressures at greater depth. He discusses neither the rate at which the process proceeds nor the expected duration of the disequilibrium pressure. A simple

model can be derived to examine the conditions for obtaining pressures at depth that are not in equilibrium with a falling water table (Appendix A). The fluid pressure response is controlled by the ratio of the change in water table depth (delta h) to the characteristic diffusion length of the porous medium during the time period of the water table decline. Diffusivities for the tuffs were used that are consistent with field measurements of hydraulic conductivity and with inferences from well responses to earth tides and atmospheric loading (Galloway and Rojstaczer, 1988). Based on this analysis, it seems improbable that disequilibrium pressures of the magnitude anticipated by Szymanski (1989) will develop.

Two types of time dependent fluctuations in water levels are expected by Szymanski: 1) a long-term decline in fluid pressure as the water table falls due to fracture dilation, and 2) short-term oscillations in response to ongoing strain readjustment above the surface Z, where limit equilibrium conditions are assumed to exist. Whether these fluctuations can be distinguished from those caused by other effects is an open question.

The monitoring period needed to detect the expected long-term decline in water levels is unclear. Assuming a tectonic cycle lasting 10^4 years, and a water table decline of 300 m due to extensional dilation, the average rate of decline is 3 centimeters/year. To identify this signal among the many factors that cause water levels to fluctuate in wells would likely require monitoring over many years, not one or two years. The discussion in section 4 of Szymanski's report suggests that he thinks otherwise.

Szymanski expects short term temporal fluctuations in fluid pressure above the surface Z(x,y,t), with a corresponding absence in pressure fluctuations below the surface, to be a diagnostic feature of a deforming fractured medium. To be diagnostic, the pressure fluctuations would need to be of considerable magnitude (corresponding to hydraulic head changes of at least several meters), and to appear as randomly distributed spikes in a continuous water level record. We return to this point in section 5.6.3 of our report.

<u>Water Table Gradients and a Water Table Rise</u>. In Szymanski's (1989) conceptual model, a steep gradient on the water table is correlated with lateral variations in the depth to the surface Z(x,y,t). Thus, a large gradient on the water table coincides with the transition from a region where limit equilibrium conditions do not exist (and the

hydraulic conductivity of the tuffs is low), to a region where the bulk hydraulic conductivity is increased due to the increased aperture of fractures. The higher hydraulic conductivity allows for lateral fluid flow in the tuffs under a reduced hydraulic gradient. This hydraulic response of the water table is a possible, but not unique, explanation of a steep water table gradient in a region where lateral flow is dominant.

The panel majority does not think that the scoping calculation presented in section 3.3.5 (Szymanski, 1989) properly characterizes the magnitude of the maximum rise of the water table at the end of a tectonic cycle. The water table rise is calculated assuming two components are involved:

1) the first component is related to the disequilibrium pressure postulated to exist between zones I and III. Should there be a large scale restructuring of permeability in the tuffs following seismic rupture, the panel agrees with the magnitude of the water table rise predicted by the calculation, but disagrees that the rise will occur on the time scale envisioned by Szymanski. We interpret this component in terms of a long-term recovery of the water table in response to a restructured hydraulic conductivity field. With the hydraulic conductivity of the tuff returning to its unstrained state, the water table would rise to the level needed to deliver upslope recharge fluxes through to the discharge area (i.e. the water table position at the beginning of the tectonic cycle).

2) the second component is a shorter-term phenomenon, related to the reduction in pore volume as strain is released. In Szymanski's model, this component drives the water table above the position needed to transmit the recharge fluxes, and so it decays through time back to that level.

It is not clear why the author has chosen to compute the water table rise in terms of the ratio of storativities in the strained and unstrained state, multiplied by the hydraulic head difference between the strained and unstrained regions. Support of this calculation, when considered for a representative volume of the rock mass, is not offered in the report. The increase in fluid pressure in the zone between the water table and Z surface, following release of strain, is a function of the effective porosity of the tuffs, the effective bulk modulus of the saturated porous medium, and the magnitude of the strain release. The panel expects this pressure increase to be relatively small (say, less than 1 MPa) unless all the strain goes into closing fracture apertures (joint stiffness calculations suggest this is unrealistic), and the

effective porosity of the tuffs is much less than current estimates. Furthermore, the maximum pressure increase (as an equivalent hydraulic head) does not translate into a water table rise of the same value. Even neglecting lateral flow, the pressure at depth is mitigated by vertical diffusion.

The panel notes the calculations recently reported by Carrigan and others (1990). These scoping calculations are intended to evaluate the effects on the water table of mechanical coupling between an elastic rock mass and the groundwater flow system. Carrigan and others (1990) use a plane strain boundary element code to compute the mean strain changes caused by one m of slip on a buried vertical fault (corresponding to a magnitude 6.8 earthquake) and by a dike inflation of four meters. The undrained (instantaneous) pore pressure changes caused by these mean strain changes are used as initial conditions in a hydrologic finite element code (NORIA) to determine excursions of the water table. Permeability is not coupled to the strain field. Carrigan and others (1990) investigate a range of permeabilities including a 10^4:1 enhancement of vertical permeability in a narrow fault zone. In no case did the predicted water table rise exceed 15 meters.

These calculations are based on a model of the rock mass as a permeable porous medium. In addition, Carrigan and others (1990) estimate the effect of fracture flow on the water table rise. More specifically, they determine the volume of groundwater that could be delivered through a network of vertically-oriented fractures to a level 250 m above the normal water table. Using matrix properties characteristic of the Calico Hills (vitric) Formation in the region below the water table and a crack distribution consistent with published data, they establish an upper bound of 0.25 m^3 of groundwater per m of fault length. This bound is, however, sensitive to the aperture assumed for fractures which Carrigan and others (1990) take to be 27 microns, corresponding to the largest values measured in core samples.

The calculations of Carrigan and others (1990) suggest that although normal faulting and dike emplacement can generate large pore pressure changes at depth, the maximum water table rise is strongly limited by the volume of water that is available. Thus, their calculations support the expectation that water table rises will not be as large as claimed by Szymanski.

Recognition of a Deforming Fractured Medium. Any pattern in the spatial variability of hydraulic conductivity, either laterally or with depth, must be viewed as a weak test

for recognition of the presence of a deforming fractured medium. In Szymanski's concept, above the surface Z, there is an upward increase in hydraulic conductivity that reflects the extent of fracture dilation. Below the surface Z, hydraulic conductivity is uniformly low, with the magnitude determined by the value of residual aperture. Many factors, however, determine the spatial variability in the hydraulic conductivity of fractured rock, not aperture alone. Even within a single rock unit, hydraulic conductivity variations commonly range over 4 or 5 orders of magnitude. Hydraulic conductivity typically decreases with depth, as fracture density decreases and the lithostatic load increases. Of course, in and around through-going faults, higher permeability can be encountered at considerable depth. The pattern of hydraulic conductivity variations would likely be diagnostic of tectonic control only if strong correlations with the distribution of *in situ* stresses could be demonstrated, beyond the variation attributable to lithologic factors.

Thermal Models. Szymanski (1989) specifies a high and spatially heterogeneous heat flux to establish coupling between the hydraulic and thermal regimes. In his model (Szymanski, 1989; section 3.4.1), a non-uniform planar distribution of temperature in the lower crust drives transient hydrothermal convection within the upper crust. However, the panel majority sees no need to invoke a linkage between thermal conditions in the shallow subsurface beneath Yucca Mountain and localized convective processes in the upper mantle to explain the thermal regime in the vicinity of Yucca Mountain.

Heat flow in the vicinity of Yucca Mountain, beneath the carbonate aquifer, is likely to be in the range characteristic of the Basin and Range (approximately 90 ± 18 mW/m^2). Geologically recent volcanism to the west of Yucca Mountain, in Crater Flat, also suggests relatively high heat flow in the region. Heat flow measurements indicate considerable advective redistribution of heat by groundwater flow in the saturated tuffs and carbonate aquifer. Topographic relief, complex structural arrangements of higher and lower permeability zones, and heterogeneity in the thermal conductivity structure also promote lateral temperature gradients. Given these factors, we do not attach any special significance to lateral temperature gradients that occur in the region at and immediately below the water table.

Our discussions with Jerry Szymanski made it apparent that, in his opinion, hydrothermal convection is a common phenomenon in the Death Valley - Nevada Test Site area. This opinion is based on the general nature of the tectonic setting, and his

interpretation of surface discharge features (e.g., thermal springs). Although Szymanski claims that at certain times conditions at Yucca Mountain are such that the Rayleigh number exceeds that marking the onset of hydrothermal convection, this statement is not supported by a numerical evaluation of the Rayleigh number. Furthermore, while the concept of a critical Rayleigh number has utility in describing highly-idealized systems, application of this concept to field-based problems is often inappropriate. The Rayleigh number is valid only for the geometry and boundary conditions assumed in deriving the stability criterion.

It is difficult to either confirm or refute the presence of convective circulation on a site-by-site basis without detailed hydrogeologic and thermal studies. However, hydrothermal convection is not the only mechanism that explains the origin of thermal springs. Many low to moderate temperature thermal springs in the Basin and Range can be explained adequately in terms of advective heat transfer by the regional flux of meteoric water originating in topographically higher areas of a basin, with upflow occurring along permeable faults. Buoyancy forces related to fluid density variations and reduced fluid viscosity at higher temperatures, assist, but do not drive the fluid circulation. In Szymanski's terminology, this is a forced convection system.

Convective circulation is more often linked to a local heat source at shallower depths. Szymanski refers to a system where the dominant driving force is buoyancy due to spatially variable fluid density as a "mixed convection system". Mixed convection systems, in Szymanski's concept, occur with the transient input of heat from deeper crustal levels, which in turn originate from mantle convection. The thermal model adopted by Szymanski represents the subsurface in terms of two zones, separated by a surface $Z_c(x,y,t)$ that varies through time (Szymanski, 1989; section 3.4.4). Above this surface, coupled flow occurs as convection in faults and is a transient process; below this surface, the medium behaves as a porous medium, with a bulk hydraulic conductivity that is low. Below the surface Z_c, convection is a steady state process because the thermal interactions between convecting fluid and host rocks do not influence the convection process. There is an inconsistency in this model: if the rock mass below the surface Z_c is permeable enough to support an active hydrothermal convection system then, above this surface, there is no reason to expect convection to be restricted to through-going fault zones.

Szymanski adopts a model published by Murphy (1979) as the basis for characterizing hydrothermal convection within a fault zone as a cyclic and transient process. While

this study provides a useful framework within which to view the physics of the process, great care must be exercised in applying the results to the description of conditions that exist at Yucca Mountain. Murphy (1979) examined conditions favoring stable and transient convective circulation. For a wide fault zone with an effective permeability exceeding 10^{-15} m^2, regional geothermal gradients ranging from 30 to 60 ^{o}C/km, and wall rocks of low thermal conductivity, convection cells within the plane of the fault are predicted to develop.

Murphy's (1979) analysis assumes that fluid input to a fault zone is zero. However, fluid fluxes that originate from recharge of meteoric water in topographically higher areas of the basin move laterally through the tuffs and carbonate aquifer. This fluid flux is likely to exert a key influence on the character of heat transfer in a fault zone. The model Szymanski adopts treats the rock mass within which the fault is located as impermeable, and therefore, cellular convection does not have to compete with fluid fluxes driven by the topographic gradient on the water table. The regional fluid flux may distort, or even eliminate, the pattern of fluid flow predicted to occur under the influence of fluid density gradients.

The presence of geologically recent volcanism to the west and southwest of Yucca Mountain requires that the possibility of hydrothermal convection beneath Crater Flat be considered. Computer simulations of hydrothermal circulation related to a single intrusion of magma suggest that the active life of a convection system is on the order of 10^5 years (see discussion in Forster and Smith, 1990). Circulation extends to 10^6 years, but after 10^5 years, topographically-driven groundwater flow may mask underlying, less vigorous convection cells. If there is renewed volcanism in Crater Flat, it is reasonable to anticipate the potential for changes in the saturated groundwater flow system. To the our knowledge, no studies have yet addressed this issue.

<u>Effective Thermal Conductivity</u>. Szymanski's (1989; sec. 3.5.2) description of the stress-dependent enhancement of effective thermal conductivity is in error. He states that a time dependent dilation of the fractures will increase both the effective thermal conductivity and the bulk volumetric heat capacity of the tuffs. He acknowledges that the "apparently" larger thermal conductivity would be due to the *in situ* enhancement of advective fluid velocities. However, it is incorrect to assign the effect of this heat redistribution to conduction, which is a process different from

advection. Heat conduction is a diffusional process; it is influenced by the magnitude and spatial variability of the thermal conductivity and specific heat of the saturated rock mass. Advection of heat is governed by the direction and the magnitude of the fluid flux. The concept of a cyclic pattern in temporal variations of the thermal conductivity is not on sound theoretical grounds.

The extra porosity created by fracture dilation will not increase the bulk thermal conductivity of a unit volume of the saturated tuff; the thermal conductivity of water is less than that of the rock matrix. Here we use the term thermal conductivity in the conventional sense. The specific heat of the unit volume will increase because of the higher value of the specific heat of water, in comparison to that of rock, but only to the extent that the pore volume increases. This change is not likely to alter appreciably the specific heat capacity of the tuffs. We do not agree with Szymanski's statement that in the dilated system, large amounts of thermal energy are held in temporary storage.

Szymanski claims that the heat flux at the ground surface will increase because of a time-dependent increase in the effective thermal conductivity of the saturated tuffs. On the basis of this assumption, he expects the consequent removal of thermal energy to lead to a time-dependent reduction in the vertical geothermal gradient. The surface heat flux will <u>not</u> increase because of fracture dilation. Assuming fracture dilation did lead to an appreciable increase in the bulk permeability of the tuffs, and the combined effect of changing permeability and hydraulic gradient resulted in higher fluid fluxes during the transient readjustments to the new conditions, then the higher fluid fluxes would transfer heat either laterally, or vertically downward toward the regional groundwater flow system. Model calculations would be needed to estimate the magnitude of the reduction in the surface heat flux.

Because of the error in defining the thermal conductivity of a deforming fractured medium, Szymanski also mistakenly claims that the intensity of terrestrial heat flux is underestimated by 50 to 100% since lab-scale measurements do not sense the "effective thermal conductivity" (p. 3-84). Except in cases with complex hydrogeologic disturbances, lab-scale measurements of thermal conductivity, coupled with a complementary analysis of advective heat transfer, allow the value of the terrestrial heat flux to be estimated with reasonable accuracy.

It is implied (Szymanski, 1989; p. 3-89) that at an advanced stage of dilation, below the water table but above the surface Z, convection in faults is damped because

of the tendency for strong fluid - wall rock thermal interaction. This may be the case, but not for the reasons implied by Szymanski. In his considerations, the strong wall rock thermal interaction presumably comes about from the enhanced "effective thermal conductivity"; that is, greater rates of conductive heat transfer from the fault into the surrounding rock mass. However, as argued earlier, the thermal conductivity of the rock mass will remain essentially constant. If the tuff permeability is high, fluid fluxes that are driven by the topographic gradient on the water table and which enter the fault zone are likely to eliminate convective circulation patterns.

The Basal Boundary Condition. The issue of the appropriate hydraulic and thermal conditions to apply at the base of any model of groundwater flow at Yucca Mountain is an important one. Szymanski (1989) allows the lower boundary of the domain to be hydraulically and thermally open and to exhibit transient variations in flux rate (with hydraulic sinks and sources reflecting down- and up-flowing limbs of deep-seated convection cells). There is little discussion by Szymanski of the hydrogeologic conditions below the base of his conceptual model of groundwater flow at Yucca Mountain. It is his expectation that convective circulation occurs in the basement rocks. Little is known of the hydrogeologic system below the carbonate aquifer, so all analyses must be viewed as speculative. While a lateral temperature gradient creates spatial gradients in fluid density that drive convective circulation, the presence of a lateral thermal gradient is alone not sufficient grounds to assume that the thermal regime is markedly different from that expected under conditions of conductive heat transfer. The advective redistribution of heat by convective circulation depends upon the magnitude of the fluid velocities, a linear function of the bulk permeability of the rock mass.

If the bulk permeability of this lower region is less than 10^{-18} m^2, then it is probable that the fluid flux there can be neglected in the context of site suitability to host a repository, although the small flux may still be sufficient on a geologic time scale and under certain conditions to influence such factors as isotopic ratios. The placement of the boundaries shown on Plate 3.4.4-3 is arbitrary, and simply signals that the boundary has not been placed at a depth great enough to capture the full depth extent of any significant fluid fluxes. Szymanski is correct in stating that to represent only a piece of the flow system, it is necessary to incorporate a

space-variable flux boundary. The panel does not see this as a major issue, but rather one of correct modeling practice. It is appropriate within the context of site characterization that questions be raised about hydrogeologic conditions and fluid fluxes in the rocks underlying the carbonate aquifer.

Calculation of the Water Table Rise Due to Thermal Effects. In section 3.4.4, Szymanski (1989) attempts to estimate the magnitude of a water table rise induced by the onset of convection. Two components are evaluated: 1) that due to the thermal expansion of water, and 2) that due to the increased volume of fluid in transit through the region occupied by a convection cell. The calculation of the second component of the water table rise appears arbitrary and it does not capture the physics of the process. The logic of the calculation, as understood by the panel, is as follows. Prior to the onset of convection, a 50 meter lateral gradient on the water table is needed to move the regional fluid flux through the rock mass which subsequently will contain the convection cell (this distance is assumed to be 5 kilometers). If twice the fluid flux moves upward in the convection cell, then that corresponds to a 100 meter lateral gradient on the water table. On this basis, a 100 meter rise in the water table is predicted. The rationale for assuming that these two driving forces are equivalent is unclear. The calculation proposed by Szymanski provides no guidance in assessing the magnitude of this effect. However, the panel is not aware of any investigations of the response of a water table to the onset of hydrothermal convection.

Earthquake Processes. The panel finds little basis in observation or theory for Szymanski's concepts of earthquake processes. According to Szymanski's concept (Sec. 3.3.2.2), the characteristic earthquake is primarily a device for causing large wall-rock separations (p. 3-25). He repeatedly (p. 3-24 & ff., p. 3-29) emphasizes the importance of these separations. Indeed, he says (p. 3-24): "Without such separations, these considerations are null and void." Szymanski evidently attaches such significance to the wall-rock separations because he views them as essential for restructuring the strain field. Large wall-rock separations on widely spaced fractures cause compression of fractures in the intervening material that have dilated because of extensional straining during the interseismic period. The closure of (predominantly) vertical cracks causes a decrease in storativity. Details of the earthquake process

are regarded as incidental: "It is not of particular importance, therefore, to know a lot about this earthquake, including a) exact magnitude and focal depth; b) slip mechanism; c) stress drop and seismic moment; and d) details of physics of the nucleation process" (p. 3-29). This point-of-view is difficult to understand since it is these factors that control the magnitude and distribution of strain changes.

The mechanism by which wall-rock separations occur is also regarded as unimportant by Szymanski. But, given the at best arguable evidence for such features (see section 5.3.2, Faults and Fault Features), the absence of a credible mechanism further undermines his conceptual model. Szymanski offers only a single possibility: large wall-rock separations are the result of a large pressure pulse created by the collapse of a dilatant zone at depth. This assertion is based on his assumption "that the dilatancy/fluid diffusion model, as proposed by Scholz et al., 1973, provides a representative description of [the] earthquake nucleation process" (Section 3.3.2.2, p. 3-19).

Although the dilatancy-diffusion hypothesis seemed promising in the early 1970's, it is not now regarded as typical of the earthquake nucleation process. It is not possible to say that this mechanism never occurs, but it is thought to be, at most, highly unusual. There are several reasons for rejection of this mechanism. The most significant is that the observational support for it was not confirmed by subsequent investigations. Whenever careful, well-controlled searches for wave speed travel time anomalies were conducted, the observed changes in travel time ratios were either extremely small or non-existent. Most of the original anomalies reported are now thought to have resulted from mislocations in the depths of small earthquakes used to establish the anomaly or from unrecognized path effects.

Another argument against this hypothesis is the high deviatoric stresses required to produce dilatancy in laboratory specimens. These pressures are typically in excess of two-thirds of the peak stress, or 500 to 1000 MPa, for confining pressures representative of shallow earthquake depths. Stress changes during the earthquake cycle must be on the order of stress drops, i.e., 1 to 10 MPa. As Sibson (1990) has noted: "There is now considerable doubt as to whether this type of dilatancy is widespread in nature, because the requisite stress levels are unlikely to be maintained around established fault zones." Even if the ambient stress level is high enough that small stress changes will cause dilatancy, the dilatancy produced by such small stress cycles is much less than that predicted from fracture of intact specimens. In

addition, laboratory tests (e.g., Zoback and Byerlee, 1975) suggested that the deviatoric stress needed to cause dilatancy was not substantially reduced by repeated cycling.

Yet another argument against the dilatancy-diffusion hypothesis is the absence of a mechanism of extending inelastic deformation laterally from a fault to a large volume, as is necessary for dilatancy to occur in such a volume. Once a fault is formed, inelastic deformation tends to occur there before it does in the surrounding material. One possibility for spreading deformation laterally from a pre-existing fault zone was though to be dilatancy hardening (Rice, 1975). However, detailed analysis of this mechanism (Rudnicki, 1984; Bowers, 1982) showed that even with quite small differences in strength of the material in the fault zone and that surrounding it, it was not possible to cause any significant spreading of inelastic deformation.

In panel discussions, it was pointed out that the deviatoric stresses required to produce slip on a fault that is unfavorably oriented with respect to the stress field approach those required to fracture intact rock. The Stage Coach Road fault was noted as a possible example. It seems unlikely, however, that a fault would remain a durable feature of the landscape in such an unfavorably oriented stress field; faults in other more favorable orientations are likely to develop to accomodate the imposed deformation.

The panel majority believes that the occurrence of dilatancy diffusion and seismic pumping at Yucca Mountain is possible but unlikely. More importantly, even if these processes were to occur, the magnitude of the effects that accompany unloading of a dilatant zone at depth would be much smaller than assumed by Szymanski. Such unloading would increase the pressure in this zone, but probably by only a few MPa. The pressure increase at the fault zone would be less than this. Fluid flow, even along a permeable channel formed by the fault zone, would be at rates much less than envisioned by Szymanski. Generous estimates of the amount of fluid expelled by unloading of a dilatant zone at depth suggest that the volume of fluid would not be sufficient to raise the water table more than a few tens of meters even if lateral flow is neglected.

As already mentioned, Szymanski apparently views large wall-rock separations as essential for restructuring the strain field. This is, however, not the case. An earthquake, even without accompanying wall-rock separations, will restructure the strain field, though not necessarily in the manner assumed by Szymanski (surface parallel compression).

Comparison of surface deformation accompanying earthquakes with theoretical solutions has demonstrated that earthquake strain fields are reasonably well-described by solutions for slip on surfaces in an elastic half-space. Although the solutions are complicated by effects of the free surface and finite extent of the slip surface, the pattern of volume strains is basically quadrantal. That is, quadrants of volume increase (dilation) alternate with quadrants of volume decrease (compression). Thus, the tendency is for pore fluid to be driven from regions of compression to regions of dilation. In an elastic full space, solutions for slip produce zero net volume change (the magnitudes and extents of compression and extension exactly cancel) and there is no tendency for net fluid flow.

It is true, however, that normal faulting earthquakes that are shallow or intersect the surface cause predominantly compression in the near surface regions, particularly in the hanging wall block. Other regions are in dilation and the pattern becomes more complex with depth. Near surface compression is consistent with Szymanski's view and with observations of fluid outflows accompanying normal faulting earthquakes. But the magnitudes of the strains (generally less than 10^{-5}) are too small to effect the fluid flow anticipated by Szymanski.

5.2.2 Issues of Secondary Concern

Models of Fluid Flow in the Vadose Zone. There is an error in the author's definition of the water table and the interpretation of Plate 4.2.3-1 (Szymanski, 1989). The water table is defined as the surface on which the fluid pressure is exactly atmospheric. Except for entrapped air, the region below the water table is saturated. It is inconsistent with the theoretical foundations of saturated/unsaturated flow to state that "the water table will be considered as a plane below which most of the fractures contain water, but the rock matrix is not always fully saturated." Sampling problems may have contributed to the observed variations in saturation in the region below the water table (Plate 4.2.3-1). Szymanski's definition of the water table is incidental to examination of his conceptual model, as he has adopted water table maps published in other reports that were based on observations of standing water levels in wells.

In describing his conceptual model of groundwater flow in a deforming fractured medium, Szymanski assumes that, as fractures dilate in the vadose zone, fracture flow

will tend to develop in preference to interstitial flow through the rock matrix (Szymanski, 1989; section 3.3.5). A comprehensive understanding of the mechanisms of fluid flow in unsaturated fractured rock, of matrix/fracture interactions, and of the spatial/temporal recharge fluxes through the vadose zone has yet to be developed. Several models are being considered, each of which may be operative at different times as surface hydrologic conditions change. One model proposes that the fractures are unsaturated and that any water moving downward through the vadose zone must do so through the rock matrix, where permeabilities are higher. In this case, dilation of the fractures will not increase flow through the unsaturated fractures. A second model is based on saturated flow through fractures, which occurs during favorable but infrequent precipitation events that promote saturation of fractures at the ground surface. Fracture flow could permit fluid penetration significant distances into the vadose zone on a short time scale. Szymanski does not discuss his concept of fluid flow in the vadose zone in terms of the most recent viewpoints on mechanisms of saturated flow and infiltration through the vadose zone.

In discussions with Szymanski, he agreed that the assumption made on fluid movement through the vadose zone is not critical to evaluation of the larger-scale question of tectonically-controlled groundwater flow in deforming fractured media. He indicated that the motivation for adopting this model of fluid flow in the vadose zone was to flag a concern with respect to groundwater travel times in the vadose zone. Because this submodel is not directly of concern to his overall concept, the panel simply notes this point but will not pursue this issue further.

<u>Coupling of the Hydrologic and Thermal Systems</u>. The equation for the specific discharge of fluid (Szymanski, 1989; p. 3-58) is misleading in representing the primary nature of the coupling between the hydrologic and thermal fields. This equation is:

$$q_f = -L_1(dh/L) - L_2(dT/L)$$

This equation implies that the coupling comes about from the coefficient L_2, where the driving force is the temperature gradient ("thermo-osmosis"). The author states that in a volcanically active area, the component L_2 dT/dL must be considerable relative to L_1 dh/dL. Here L_1 corresponds to hydraulic conductivity. However, the significant coupling is already incorporated within the hydraulic potential term, which includes both pressure gradients and buoyancy (through the variation in fluid density

due to spatially varying temperature). Thus, cross-coupling coefficients are not needed to link the hydrologic and thermal fields. Neuzil (1986) reviews cross-coupling phenomena in the context of sedimentary environments. He quotes work that indicates thermo-osmosis is significant only in low permeability media (e.g., clays), and even then only when thermal gradients are on the order of 1 ^{o}C/m.

Szymanski (1989; p. 3-57 and Plate 3.4.2.2) presents a mathematical model for the simultaneous flow of fluid and heat (as given by Thunvik and Braester, 1982). This model does not incorporate the cross-coupling process referred to in the previous paragraph. The author needlessly confuses the discussion of thermal-hydrologic coupling by implying the cross-coupling terms are the dominant factor in this linkage.

The representation of simultaneous heat flow and fluid flow in terms of cross-coupling equations, and the panel's disagreement with it, does not bear on an evaluation of the author's conceptual model. No calculations are made with the cross-coupled equations. The panel agrees that there will be the simultaneous transfer of heat and fluid, and that it is given by the equations on Plate 3.4.2.2.

The statement is made (Szymanski, 1989; p. 3-69) that because gradients of temperature are not colinear with gradients of hydraulic potential, buoyancy gradients are considerable relative to hydraulic head gradients. Szymanski infers from this that the dominant mode of transport of terrestrial heat is mixed convection and implies that forced convection is of less importance. It is incorrect to make such an inference. Buoyancy forces will be the strongest where the thermal gradient is the steepest. The interplay of advective heat transfer and hydrothermal convection must be evaluated within the framework of the entire flow field, both hydraulic and thermal, and not on a point to point comparison of the colinearity of hydraulic and thermal gradients.

<u>Z Surface</u>. Szymanski's discussion of the downward movement of the Z surface as caused by extension (strain) is inconsistent with the model shown in Plate 3.3.2.2-5. (In Szymanski's concept, the Z surface divides shallower material that has reached limit equilibrium conditions from deeper material that has not.) The upper picture of Plate 3.3.2.2-5 shows the "undeformed state" (actually the state at the beginning of the tectonic cycle) of the material subjected to a depth independent extension rate ε_{xx}. But the lower diagram shows only the material above the Z surface as extended. If the model is indeed subjected to a depth-independent extension, then the material both above and below the Z surface must be extended the same amount (though the extension

of the deeper material may not be accomodated by fracture). These diagrams are consistent only if a depth-dependent reduction in horizontal stress is imposed. Then, as described by Szymanski, the increase in overburden stress with depth allows limit equilibrium conditions to be met in shallower regions earlier than in deeper regions. As depicted in Plate 3.3.2.2-5, this predicts an extension that decreases strongly with depth (even allowing for the increase in modulus with depth). Although it is reasonable that the larger scale tectonic processes result in an extension rate that is approximately uniform with depth (over the scale of Yucca Mountain), it is more difficult to conceive of these processes causing a depth independent reduction in horizontal stress, as implicitly assumed by Szymanski.

Isotropic and Singular Points. In discussing the heterogeneous stress field around fractures, Szymanski (p. 3-20) adopts the terminology used by Ramsey (1967) of "isotropic" and " singular" points. At an isotropic point the principal stresses have equal values. According to Ramsey (1967, p. 43), a singular point is the special case of an isotropic point at which the values of the principal stresses are zero, but Szymanski uses the term in the less restrictive sense of a point "where the mean stress has a very small value" (p. 3-20).

Szymanski attaches great significance to the occurrence of such points, but two simple examples suffice to demonstrate that these points have limited significance for mechanical behavior. Consider, for example, the stress field near the edge of an ideal tensile (Mode I) crack in an elastic solid. If the crack faces are unloaded, then the faces are lines of singular points (both principal stresses are zero). If, however, a uniform farfield normal stress is applied parallel to the crack plane, then the faces contain neither singular nor isotropic points. Now, consider an ideal shear (Mode II) crack in an elastic solid. Lines inclined at 60° to the fracture plane are isotropic points and the line ahead of the crack is a singular point in Szymanski's terminology but not in Ramsey's (The mean stress is zero, but the principal stresses have equal and opposite values). Therefore, the occurrence of a singular point in Szymanski's definition need not correspond to an open fracture, nor does an open fracture imply the existence of a singular point.

In discussing the stress changes caused by shear displacement of a fracture, Szyamsnki (p. 3-33) correctly notes that the mean stress changes sign on the fracture faces. (A minor point is that Szymanski identifies the mean stress as (σ_1 +

$\sigma_3)/2$. This is true only if $\sigma_2 = (\sigma_1 + \sigma_3)/2$, which is the case for an elastic material with $\varepsilon_{22} = 0$ and ν (Poisson's ratio) = 1/2.) He erroneously states, however, that the stress difference $(\sigma_1 - \sigma_3)$ decreases on a portion of the fracture faces and increases on a portion. (Although Szymanski is not specific, the discussion and Plate 3.3.3.2-4 imply that he has in mind a model of a fracture with a uniform applied shear stress.) If σ_1 is the algebraically largest principal stress and σ_3 the smallest, then $(\sigma_1 - \sigma_3)$ is by definition positive and, hence, is increased everywhere by slip. It is true that the sign of the principal stress with the largest absolute value does change on the crack faces. But this feature of the solution has no significance beyond the observation, already noted, that the mean stress changes sign.

5.3 Summary of Important Geological Information

5.3.1 General

Specific geological evidence from Yucca Mountain which Szymanski considers important support for his concept consists of the faults, their fillings and breccias, and deposits of carbonate and silica on or subparallel to the present ground surface.

Broad scale evidence cited by Szymanski includes the general geological setting in the Basin and Range extensional regime and features such as geologically young volcanic centers west and south of Yucca Mountain. These features are not in dispute, though the exact processes and rates governing them may be unknown or under investigation. Other features in the region around Yucca Mountain are presented by Szymanski as field examples of the processes he proposes control the hydrology of Yucca Mountain. For example, Szymanski proposed that the Titus Canyon breccias are the result of processes he contends operate at Yucca Mountain. But he presents no written evidence concerning the age, origin, or relevance of the breccias at Titus Canyon. We do not review these geographically more remote examples although we recognize their scientific interest. We will focus in this section on the specific features associated with faults and carbonate/silica deposits supposedly derived from groundwater delivered to the surface by seismic pumping and/or hydrothermal convection along fault systems. Geochemical and thermal information about the carbonate/silica deposits are reviewed later (Sec. 5.3.6).

5.3.2 Faults and Fault Features

The important observable features of faults in Szymanski's discussion are the wall-rock separations (individual and cumulative), fault/fracture fillings, textural evidence, and the close association of faults with surficial carbonate/silica deposits. Szymanski has inferred that extension is large in the Yucca Mountain area, that large separations on faults occur during earthquake events, that color rims on surficial rock fragments or of adjacent strata indicate hydrothermal alteration, and that the textures and mineralogy of the carbonate/silica vein and surficial deposits demonstrate a deep origin of upwelling fluids along fault zones.

Wall-Rock Separations. Szymanski (1989, p. 3-23 to 3-25) believes that large wallrock separations (at least tens of centimeters) which develop virtually instantaneously are necessary for tectonic processes to dominate the hydrologic system. The requirement is emphatically stated: "To be effective, the characteristic earthquake must either produce or be accompanied by large-scale separations of wallrock. This separation ... is the essential factor in the cyclic deformation of a fractured medium" (p. 3-29). It is Szymanski's opinion that without large wall rock separations, the tuffs above the surface Z would remain in a uniformly dilated state following seismic rupture. He argues that unless extensional strain is transferred to a small number of dominating faults within the region he identifies as a structural domain, then tectonic control of the hydrologic system would not occur in repeating cycles. The massive appearance of the calcite filling the veins suggests to him that wide openings develop on the faults. The physical and chemical evidence examined later strongly support incremental deposition over a period of several hundreds of thousands of years. We do not know of any way (or need) to refute the belief that the faults had a wide separation at some time, though the breccias and laminar carbonate/silica deposits do not support such a belief.

In Szymanski's conceptual model, the separations form as a result of fault rupture and strain relief/reorganization. They provide conduits for upwelling fluids. He cites three supporting examples which most of us have visited: along Hwy 95 near Skeleton Hills, Devil's Hole, and the Furnace Creek fault (including Titus Canyon). Of course the critical example, much argued (and discussed later), is the brecciated and mineralized fault zone near the base of Fran Ridge and exposed in Trench 14 just east

of Yucca Mountain. Similar features are cited for Solitario Canyon and other faults at and near Yucca Mountain.

Extension rates across the southern Great Basin are cited by Szymanski as 0.07 x 10^{-6} per year (Wernicke and others, 1982). Szymanski (p. 3-28) estimates 10% extension for the Yucca Mountain area since the late Miocene. If we take this period as 10^7 yr, for example, the calculated strain rate is 10^{-8} per year. There is no doubt that the region, including Yucca Mountain, is subject to extension. Szymanski has discussed the Yucca Mountain area as being unique in the Basin and Range. Given the uncertainties in these numbers and probable variation in extension rates over geological time, extension at Yucca Mountain does not seem a firm basis for an unusual or unique process.

Fault and Fracture Fillings. From Szymanski's reports and discussions with him, the "floating" breccia textures loom large as evidence of high-pressure fluid discharge and rapid mineralization of fault zones. Fragments floating in the carbonate/silica deposits, by these arguments, can only indicate that fluids welled up rapidly, buoying the fragments while or until carbonate/silica minerals formed nearly instantaneously to surround and suspend the fragments. We note that, in discussions, Szymanski also believes that upwelling may occur during several episodes or over more lengthy periods, resulting in surficial discharge that continues for thousands of years. Szymanski has also stated that the stable isotopic evidence indicates that at Trench 14, for example, the exposed fault/fractures are not the actual pathway of the upwelling source. We have chosen to treat each of these differing possibilities as expressions of Szymanski's ideas. In any case, wide separations along the fault plane must be inferred to permit fragments to move or be suspended in the upwelling fluid, though we were not able to determine if Szymanski's interpretation of the suspended fragments requires the interpretation of wide separation of faults or vice versa.

Laminae of differing mineralogy and cross-cutting relationships within fault zones, as exhibited in Trench 14, suggest many small episodes of mineral formation and deposition, a feature difficult to reconcile with the idea of a massive and nearly instantaneous precipitation of minerals. It seems more likely that, with multiple fracture/faulting events, angular fragments attached to earlier cement are separated from wallrock and then re-cemented, eventually producing "floating" textures. Limited radiometric age information from Trench 14 is not very helpful in ruling out the idea

of a single massive cementing event; it is hardly necessary in view of the physical relationships. The data we have seen may not refute the claim that small increments of cement formed rapidly at Trench 14, but this is quite different from floating fragments cemented instantaneously in a wide fault opening.

Winograd and his coworkers (e.g., Ludwig and others, 1990) demonstrate that calcite accumulated slowly at Devil's Hole over a period of about 500,000 years rather than as a geologically instantaneous mineral precipitate. Although we do not believe that Devil's Hole is an analog to the Yucca Mountain deposits, it has been proposed by Szymanski as such. The laminar character of these deposits is broadly similar, however, to those of Yucca Mountain.

If the "floating" textures could be documented as having formed from a massive mineral precipitation event, the claim of wide and instantaneous separation of blocks on the fault plane would be substantiated. We do not see that the physical evidence supports this interpretation. Interpreting these textures as "floating" due to rapid mineral precipitation and suspension in a moving fluid does, however, have further limiting implications. Estimates by panel majority members indicate vertical fluid velocities of about 2-3 m/sec are required to suspend blocks in the range of 10-25 centimeters diameter. Velocities this high limit the heat loss from an upwelling fluid; either the upwelling fluid began rather "cold" (given the range of near surface and surficial temperatures of precipitation inferred from calcite stable isotopes) or the process does not occur in this fashion.

The "floating" texture by itself could be considered broadly permissive evidence of an upwelling origin and single event, though a variety of geological processes (e.g., diagenetic mineralization, pedogenesis, explosive volcanism, and unrelated processes such as debris flows and glacial dropstones) result in small to large clasts "floating" in matrix. The laminar character, ages, and mineral variability, however, are strong evidence against such an event. The fluid velocities necessary for such a phenomenon appear inconsistent with the thermal history of the deposits. The texture can be produced by processes which are consistent with the remaining evidence.

5.3.3 Breccia Formation

Szymanski (1989, p. 3-27 and p. 3-45) has identified what he calls "explosive breccias" in the vicinity of Yucca Mountain. He infers that their formation requires a large and rapid increase in pressure. An alternative explanation is that large

pressure reductions sufficient to spall wall rock are generated by rapid fault openings. Thus, even if Szymanski's interpretation of these features as breccias is accepted, they do not necessarily indicate a pressure increase of large magnitude.

This implosion model is essentially the same as that proposed by Sibson (1985, 1987) in the context of slip propagation through dilational fault jogs. Sibson (1990) has suggested this process as a possible mechanism for "floating clast breccias".

The pore pressure decrease due to opening can be estimated by assuming the fault is circular and there is a ramp increase in the opening. Our calculations suggest that if even a small opening (of the order of 1 to 10 centimeters) accompanies faulting and occurs over a time scale of the order of earthquake rise times (1 to 10 seconds), then the pore pressure decrease can be a substantial fraction of the shear modulus, sufficient to exceed the tensile strength of most rocks.

Whether opening accompanies slip on normal faults is unclear. Certainly, there is no evidence of fault openings from geodetic and seismological studies. Szymanski has, however, interpreted features in the field (for example, the feature on Highway 95 near Lathrop Wells) as evidence for large openings accompanying faulting. Some opening is conceivable by application of a seismic rebound argument to faulting in extensional regimes. More likely, opening near the surface could be generated as a result of a decrease of the fault dip with depth (listric geometry).

5.3.4 Geometry

At Trench 14 and Solitario Canyon, the geometry of these carbonate/silica units can be examined. Mineralization within the fault at Trench 14 shows recemented areas and appears partially truncated by surficial carbonate/silica deposits, ruling out a single formative event. The surficial deposits are thicker and more continuous on the downslope side of the fault. On the east side of Busted Butte, the surficial carbonate/silica is continuous upslope of the observable subvertical fracture/fault mineralization. Szymanski and panel members agreed during discussions that stable isotope evidence shows the observed vertical vein fillings at Trench 14 are not the upwelling source of the adjacent surficial deposits. Any upwelling source would have to be uphill of the surficial deposits. At least for the moment, these observations preclude using the geometry as evidence of the upwelling origin of the deposits.

During a recent (July, 1991) field trip, the panel majority observed the additional deposits exposed by deepening Trench 14. We noted that the carbonate/silica vein

material is much narrower at depth than it is near the surface, though its overall character seems little changed. These physical features do not change our understanding based on the near-surface relationships. The isotopic evidence should be of interest, though physical continuity suggests there should be little difference from higher samples.

We examined the surface exposures upslope of Trench 14 without observing any likely evidence of a pathway for upwelling fluids consistent with Szymanski's conclusion that the Trench 14 fracture and vein filling do not represent the upwelling pathway for the source fluids.

5.4 Stress

The state of stress at Yucca Mountain and differences in the stress there from adjacent regions are lines of evidence that Szymanski cites in support of his concept. Two sets of data on the stress state are considered. The first set is hydraulic fracturing measurements reported by Stock and others (1985, 1986). The second set is based on inferences drawn from borehole injection tests.

Hydraulic fracturing measurements at Yucca Mountain indicate that the minimum horizontal stress is low, less than half the vertical stress. This is typical for extensional environments. The stress state at Yucca Mountain does differ from those at Rainer and Aqueduct Mesas and at Climax Stock. The correlation of low hydraulic conductivity in the tuffs there with larger minimum horizontal stress values is interesting, but a variety of factors including lithology, topography, and tectonic history could contribute to the observed relation. As summarized in plates 4.2.5.4.-98 and -99 of Szymanski's report, the hydraulic fracturing measurements do lend some support for a difference in conditions at the north and south ends of Yucca Mountain. Nevertheless, these current spatial differences do not necessarily reflect different positions in time of a cyclic process, as implied by Szymanski (p. 4-45). Given the typically heterogeneous conditions within the Basin and Range, it is not surprising that the stress state at Yucca Mountain varies spatially and differs from that of nearby regions. The spatial variation at Yucca Mountain would be more significant if it correlated well with hydrological conditions as asserted by Szymanski (Sec. 4.2.2, 4.2.6). The panel does not believe, however, that the data are adequate to indicate such a correlation.

According to Szymanski's concept, conditions of limit equilibrium should be met near the surface but not at depth, with the transition defining the Z surface. Szymanski (1989; p. 3-19) defines limit equilibrium as "the *in situ* stress conditions where a) shear stress along some fractures is equal to the frictional resistance of these fractures, this means that locally the Coulomb-Navier criterion for shear failure is satisfied and b) local shear displacement along some fractures exceeds the peak-shear displacement." Thus, if the peak shear strength is identified with the frictional resistance in the Coulomb condition, a) and b) are synonymous, and it suffices to regard limit equilibrium as satisfying Mohr-Coulomb conditions. More specifically, for appropriate orientations the resolved shear stress is equal to a friction coefficient multiplied by the effective normal stress (total stress minus pore fluid pressure) plus cohesion (which probably can be neglected here). This condition pertains precisely to a through-going, non-slipping fault in a homogeneous stress field. Although the usefulness of this criterion as an approximate indicator of failure is well-established, one should be properly cautious of applying it to faults of finite length in an already fractured medium.

Identification of the Z surface from the hydraulic fracturing measurements is ambiguous. Only the measurements from UE-25p#1 show a clear transition with depth from meeting conditions of limit equilibrium to not meeting them. In USW G-1, one of the three measurements shown in Plate 4.2.4.4.-98 as above the Z surface does not meet limit equilibrium conditions and one of the three measurements shown as below the Z surface does. All measurements in USW G-3 are at limit equilibrium; all those in USW G-2 are not. Consequently, additional measurements with depth would be useful.

Szymanski also admits that above the Z surface, but away from fractures which are dilated, stress conditions quite far removed from limit equilibrium could be observed. These conditions apply at different points within a rock mass viewed as existing at the same stage of the proposed tectonic cycle. In discussions, Szymanski proposed characteristic distances between dilating fractures on the order of perhaps tens of meters. Thus, with sparse data, it would be difficult to confirm or refute the representation of the Z surface.

The hydraulic fracturing measurements do indicate that Mohr-Coulomb conditions are met below the water table. Szymanski infers from this (and other evidence) that Yucca Mountain is late in his tectonic cycle and that a large earthquake is imminent. In discussions with the panel, he has used terms such as "unstable" and "pregnant" , and

in his report (p. 4-21) he characterizes the stress system at Yucca Mountain as "delicately balanced." There is no basis for these interpretations. As already noted, the measurements simply indicate that the minimum horizontal stress is low, as is typical of extensional environments. Furthermore, while satisfaction of the Mohr-Coulomb conditions indicates a potential for slip on appropriately oriented faults, it gives no indication of the stability of slip. That is, failure could occur aseismically or seismically, by means of large numbers of small earthquakes or by episodic large earthquakes. Thus, inferences that the system is "unstable" or "delicately balanced" seem unwarranted.

The stress state inferred from the hydraulic fracturing measurements is well accepted even if the implications of the stress state are arguable. Although there is inevitably some degree of art required in obtaining good hydraulic fracturing measurements, the basic procedure has been validated by years of experience and comparison with other measurements, both in the field and in the laboratory. In contrast, Szymanski's interpretation of the borehole slug tests is novel.

The borehole injection tests provide an opportunity for insight to the *in situ* stress conditions. At Yucca Mountain, these tests were carried out with initial pressure heads as high as 500 meters above the equilibrium value. Szymanski equates the break in slope seen in the injection data to correspond to a minimum value for the closure pressure (his so-called type B curves). There is some support for this interpretation. The results of the hydrofrac measurements at Yucca Mountain suggest that if initial water levels in the injection tests are 400 to 500 meters above the equilibrium pressure, then within the injection interval the fluid pressures should exceed the value of the closure pressure early in the test. This kind of response is not unique to Yucca Mountain; it is reported elsewhere in the literature in conjunction with deep well injection. The panel majority is of the opinion, however, that quantitative interpretation of the injection test data is not as straightforward as implied by Szymanski.

Szymanski (1989; p. 4-39) notes two advantages of the borehole injection tests: "First, in contrast to the hydrofracture measurements, the injection tests emphasize areas where the *in situ* values of closure pressure are lowest. Second, large segments of a borehole are involved in testing." Whether these are indeed advantages is questionable. Because these tests monitor the pressure decay due to injection of a fixed amount of fluid, it is not clear what portion of the fracture (or fractures,

since the packed-off intervals in these tests were large) the test is sampling. It may, in fact, be sampling only a small, non-representative, portion near the borehole. If the tests had been carried out by injection of water at a fixed rate, it could be determined whether the fracture was extending away from the borehole.

Furthermore, Szymanski's conceptual basis for interpreting these tests is questionable. He infers the closure pressure from essentially a Mohr-Coulomb analysis. As already noted, the Mohr-Coulomb analysis strictly pertains to conditions of homogeneous stress. Conditions along the fracture are likely to be highly heterogeneous and not well characterized by a single number such as closure pressure. In all likelihood, the test is preferentially seeking out open portions of fractures, and the closure pressure inferred by Szymanski pertains to those portions. Plate 4.2.5.4-96 (Szymanski, 1989) shows that estimates of closure pressure are consistently smaller than estimates based on hydrofrac tests. It is possible to question whether or not the responses in these two tests are measuring the same quantity as assumed by Szymanski.

The rapid decay of the initial water level, which Szymanski uses to infer the closure pressure, may result from encountering a highly transmissive section of a fracture (or sections of multiple fractures). Szymanski views the "statement that a highly transmissive bedrock was encountered" as "true but hollow" (p. 4-41). More balanced considerations suggest that it is not. Hydraulic conductance is determined by the connectivity of a set of fractures that undoubtedly depends on the stress in a more complex way than assumed by Szymanski. Even if the tests are interpreted in terms of the response of a single fracture, the inferences made by Szymanski are based on an overly simplified conceptual model. Unless fractures are completely open and nowhere in contact, the hydraulic aperture of a fracture differs from the mechanical aperture (Brown, 1987). Therefore, it is possible that a fracture could be highly transmissive but yet not have zero normal stress across it. This condition would result if the contact area is small and the surface roughness such that it provides little impediment to flow. In this case, Szymanski's estimate of closure pressure would be too low.

Both laboratory and *in situ* testing of fractures indicate that portions of fractures remain open at effective normal stresses appropriate to depths of more than a kilometer. This means that there are places, perhaps many, on the fracture surface where the normal stress is zero. These locations correspond to "singular points" in Szymanski's terminology. Nevertheless, the average stress across the fracture is

substantial and the joint stiffness is considerable. This observation contradicts the assertion of Syzmanski that the presence of open fractures indicates that the system is "delicately balanced".

It is significant to note that at those injection intervals classified as type C, where a comparision is possible, pumping tests and injection tests yield similar results. This behavior seems inconsistent with a so-called singular point. Pumping tests reduce fluid pressures in the rock mass; the hydraulic conductivity could be expected to decrease as the effective stress around the borehole increases. A map locating singular points (and from that the Z surface) on the basis of Szymanski's so-called type C slug tests must be interpreted with caution; they are less diagnostic than either *in situ* stress measurements, hydrofrac tests, or even the type B slug tests.

In summary, the panel sees little significance in the inferences of closure pressure from the slug tests. In addition to the conceptual difficulties just discussed, the injection test data are of questionable reliability. The results are, however, sufficiently interesting to warrant further investigation. Repeating these tests using smaller packed-off intervals and starting with small values of applied head and incrementing them would be more revealing. In addition, some numerical simulations would be helpful in understanding what these tests are measuring.

5.5 Geochemistry and Thermal Conditions

5.5.1 General Comments

In the original report and a follow-up draft (May 15, 1990) discussing geochemical information, Szymanski has interpreted carbonate/silica deposits at Yucca Mountain as formed from groundwater that welled up through fractures and faults and, in some cases, discharged at the surface. Fluid flow is driven by tectonic processes, including seismic pumping and/or hydrothermal convection. These so-called "hydrotectonic" deposits include veins within the present-day unsaturated zone that fill faults/fractures as well as surface carbonate/silica deposits and similar buried deposits (e.g., at Busted Butte) subparallel to the topography. Others who have examined these deposits and/or the data base documenting their physical and chemical properties conclude the surficial deposits are calcretes (caliche) formed in association with the percolation of rainwater through the soil profile.

In this section we first discuss a range of issues raised by Szymanski that he feels support his concept. We then present our opinions on interpretations of the various suites of isotope data.

A number of factors have been used by Szymanski in his reports and during discussions to justify an origin tied to upwelling fluids: 1) the carbonate/silica deposits are found on the downslope side of faults, 2) a paleogeothermal gradient, mainly from one borehole and based on stable isotope data (Szabo and Kyser, 1990), is higher than the present geothermal gradient in the same borehole, 3) rainfall and surface calcium sources are believed inadequate to form these as pedogenic deposits, 4) color rims on volcanic clasts near Solitario Canyon fault are attributed to hydrothermal alteration by ejected fluid, 5) isotopic data are considered to demonstrate deeper circulation and groundwater sources driven by tectonic processes, 6) tectonic conditions are believed to dominate the hydrologic system and make such processes inevitable, and 7) the vein fillings look like other hydrothermal/ore deposits formed from upwelling fluids. The first five factors are treated in this section while the last two are examined in other sections.

5.5.2 Geometry

The carbonate/silica deposits on the surface are common on alluvium and weathered zones in the region around Yucca Mountain. During discussions among the panel members, it has been suggested that the surficial deposits are thicker and mostly downslope of faults. The inference has been drawn that the fault zones are the source of upwelling fluid which deposited the carbonate and silica. We reviewed earlier in our report the relationships (e.g., Trench 14 and Busted Butte) which show surface-parallel deposits truncate or cut across vertical vein fillings and show this inference, based on geometry, is incorrect.

5.5.3 Thermal Gradients

Sass and others (1988) have compiled thermal data from numerous boreholes around Yucca Mountain. Analysis of the data lead them to the following conclusions:

1) temperature gradients in the saturated and unsaturated zone range in different boreholes from about 15 ^{o}C/km to 60 ^{o}C/km. Temperature gradients are inversely related to the thickness of the unsaturated zone (Sass and others, 1988).

2) temperature gradients measured in the upper 500 m of the saturated zone are

irregular, showing evidence of redistribution of heat by both lateral groundwater flow, and upward or downward flow in either the well bore, or in the surrounding tuffs.
3) thermal conductivity measurements from the unsaturated zone have a modal value of 1.0 W/m^{o}C for the nonwelded tuffs and 2.1 W/m^{o}C for the welded tuffs.
4) heat flow from the saturated zone at Yucca Mountain is estimated to be 40 $\pm$ 9 mW/m^2, calculated using the full depth extent of the temperature logs, and 49 $\pm$ 8 mW/m^2 using short, linear segments of temperature profiles.
5) average heat flow from the unsaturated zone (41 mW/m^2) is interpreted to vary from values similar to those of the saturated zone to as much as 20% lower. Heat transfer by vapor phase processes, and by an undetermined rate of downward fluid flow, may be responsible for the difference in values between the unsaturated and saturated zones.
6) relative to the regional heat flow of approximately 90 $\pm$ 18 mW/m^2, surface heat flow observed at Yucca Mountain is low. This difference is attributed to lateral flow beneath their depth of exploration, probably in the carbonate aquifer.

On a larger scale, we note that conductive heat flow from the unsaturated zone is lowest in the immediate vicinity of Yucca Mountain. Values are higher to the south and west (see Fig. 15, Sass and others, 1988), and to the east (e.g., a gradient of 45 ^{o}C/km in UE25a#3 in the Calico Hills, 10 miles east of Yucca Mountain).

Szymanski argues that lithostratigraphic variations in the tuffs are of minor to no importance in his conceptual model. This is certainly not the case when interpreting the geothermal gradient, where the differing thermal conductivities of the welded and nonwelded tuffs are reflected in the temperature gradients. This point is illustrated in the discussion by Sass and others (1988; p. 35), in their analysis of heat flow in the unsaturated zone using measurements made in borehole G4 (located south of the region with the steep water table gradient). Between depths of 150 and 400 m, in welded tuffs, the gradient is 17.8 ^{o}C/km. Below 400 m, in nonwelded tuffs, the gradient nearly doubles to 30.1 ^{o}C/km. Conductive heat flow (the product of the geothermal gradient and the thermal conductivity) should be approximately uniform across the section. Taking into account the different thermal conductivities, estimates of heat flow calculated for the two segments in the welded and nonwelded tuffs are in excellent agreement, demonstrating a lithostratigraphic control on the geothermal gradient.

Szymanski, in his 1989 report and in subsequent documentation supplied to the panel, places considerable emphasis on his interpretation that the paleogeothermal

gradient in the unsaturated zone is higher than the present-day gradient. Such an observation would be consistent with warmer fluids moving upward into the unsaturated zone. Because it is possible from $\delta\ ^{18}O$ data to infer the temperature at which vein-filling calcite was precipitated, using an empirical model to represent the temperature-dependent fractionation of oxygen isotopes, attempts can be made to estimate values for a paleogeothermal gradient.

The data for these calculations are given in Szabo and Kyser (1985, 1990). They list stable isotope data for 17 samples from boreholes UE25a#1, G-2, and G-3, in addition to uranium/thorium age dates for most of the samples. Samples from shallower depths are enriched in $\delta\ ^{18}O$ relative to samples from greater depths in the unsaturated zone. Szabo and Kyser (1985, 1990) believe it unlikely that an ascending fluid could evaporate sufficiently to enrich $\delta\ ^{18}O$ upward and lose CO_2 rich in ^{13}C to form these carbonates. They suggest meteoric water moved downward and formed calcite in equilibrium with a geothermal gradient; for UE25a#1, the gradient they suggest is 34°C/km, similar to the average gradient measured in the region immediately above the water table in the same borehole.

We re-examined the data (Szabo and Kyser, 1990) using the equilibrium fractionation factor of O'Neil and others (1969), and we assumed the fluid source would have constant $\delta\ ^{18}O$. The three data points for UE25a#1, including the sample from below the water table at 611 m depth, can be approximately fit using a surface temperature of 14 ^{o}C, a fluid source enriched in ^{18}O by about 11 per mil, and a geothermal gradient of 34°C/km. Some adjustments of these parameters would probably produce a better fit, but the apparent paleogeothermal gradient differs considerably from the current thermal gradient of about 22-25 ^{o}C/km in the unsaturated zone of UE25a#1. (This latter gradient is estimated using the temperature profile across the full extent of the unsaturated zone rather than the short segment apparently adopted by Szabo and Kyser.) The ages of the three samples range from about 310 ka to more than 400 ka. Thus, the available evidence from this hole suggests that, at this location, a paleogeothermal gradient was higher than the present-day value. Because the estimate of calcite precipitation temperature is based on a number of assumptions concerning the isotopic composition of the source water, surface temperature, and equilibrium fractionation, and because these data are few, there is considerable uncertainty in the determination of a paleogradient.

Individual data points for borehole G-3 can be approximated with paleogeothermal gradients (to the surface) in the range of about 22 to 30 ^{o}C/km, with some changes in surface temperatures or other factors. The samples from a short interval in borehole G-2, if they were assumed to be coeval and from a fluid source with constant isotopic composition, could be interpreted to indicate a paleogeothermal gradient of about 100°C/km. It is clearly unreasonable to extrapolate this as a gradient through the rock section, and it is likely one or both assumptions are invalid.

The paleogeothermal gradients calculated for these data, given our assumptions, suggest gradients in the range equivalent to the geothermal gradients measured in the area, with one borehole possibly exhibiting a paleogeothermal gradient higher than the present-day value. An upwelling system would have to move fluid more slowly and/or in limited volumes to more nearly equilibrate with the temperature gradients in the boreholes. In addition, most samples exceed 100,000 years in age, longer than the general period associated by Szymanski with his proposed tectonic cycle.

The vertical enrichment of ^{18}O is not consistent with rapid and large scale upwelling of fluids to the surface or near-surface regions from a source of relatively uniform isotopic content. Under those conditions, we would expect a nearly uniform vertical isotopic composition.

We emphasize the sparcity of the data base at present, and we understand that further isotopic studies of calcite veins from the unsaturated zone are underway. The limited age information for calcite precipitation, obtained with methods less sophisticated than are currently available, do not provide evidence for a tectonic cycle with a period of about 10^4 years as proposed by Szymanski, and the data do not resolve questions of other cyclicity, such as might be found from climatic effects on either infiltration or pedogenesis.

5.5.4 Calcium and Silica Sources

From the report, and especially, from discussion, it is clear that Szymanski regards meteoric processes and calcium sources inadequate in the Yucca Mountain area to account for a pedogenic origin of the carbonate/silica deposits. Szymanski argues that the rates of such processes are far too low to produce the deposits in the time available. The crucial factors to the argument are the ages and inferred rates of accumulation of the surficial carbonates, the potential sources of calcium, and the amount of precipitation and infiltration. The volcanic rocks at and near Yucca

Mountain are demonstrably low in calcium. In other areas of the southwest (e.g., Gile and others, 1981; Machette, 1985), calcium in rainfall and measured eolian sources are considered adequate for developing thick caliche. Measured modern eolian and meteoric calcium sources in the Las Cruces, NM, area would accumulate carbonate at about 20 g/cm^2 over 10^5 yr (Gile and others, 1981). A pure carbonate profile would be about 8 centimeters thick, based on these numbers. Given the normal low porosity, density, clast framework, and fine-grained impurities of these deposits, the actual soil profile might be 30 to 50 centimeters thick. Machette (1984) reviewed average accumulation rates for the southwest U.S., finding that younger soils ranged to about 45 g/cm^2 for 10^5 yr, while older soils ranged between 20 and 30 g/cm^2 for that period.

The data for Yucca Mountain (Reheis, 1984) include measured eolian sources of calcium over a limited period of time; these measurements are still in progress. The eolian component, together with solutes in rainwater, provides the equivalent of carbonate ranging from about 3 to 30 g/cm^2 for 10^5 yr. The most important factor to be assessed, therefore, is the time of accumulation for various deposits. Some deposits are too old to be dated by current radiometric methods; they cannot be evaluated for rates of accumulation. In any case, they are probably too old to be relevant to a continuing process. Other deposits have been determined to fall within the limits of age dating techniques and will require careful isotopic evaluation to determine if the time of formation is too short for pedogenic processes.

The carbonate deposits commonly have only a single date, with little or no information available to interpret such a date. As an example, site 106 (Szabo and others, 1981) has a single date for a carbonate deposit of 78,000 $\pm$ 5,000 years. We have examined surficial carbonate at or near the site of this sample. The carbonate features appear consistent with a surficial, pedogenic origin; the date seems relatively young for this calcrete. We do not have information about the sampling which allows us to infer that this age may represent the beginning of deposition, the end, or some average age for the unit. The deposit is being further examined and analyzed.

We note that in many other studies (e.g., Reeves, 1976; Gile and others, 1981; Machette, 1984), pedogenic origins are widely accepted for deposits similar in morphology to the Yucca Mountain surficial carbonate/silica beds, and the rates of accumulation are inferred from geomorphic or radiometric dating. Rate of accumulation is not a means of rejecting a pedogenic origin, unless it is demonstrated that the

period of accumulation was very short, as many contributing factors (e.g. climate, dust or other calcium sources) may differ now from earlier conditions.

In contrast, Szymanski places no apparent upper or lower bounds to the length of time or rate of formation of these deposits by upwelling mechanisms. They may form instantaneously, intermittently, or over longer periods of times (thousands or tens of thousands of years). Any rate of formation determined for these units will be compatible with mechanisms proposed by Szymanski.

The solubility of silica is relatively low in most surface waters. As a consequence, the volume of silica in the surficial carbonate/silica deposits and veins presents a concern for an origin related to pedogenic processes. At Yucca Mountain, the volcanic rocks as well as volcanic ash are sources of silica. Soils in Nevada (Chadwick and others, 1987a,b), for example, show opaline silica formed and accumulated within 30 to 50 thousand years on soils having volcanic sources of silica. Soluble silica, which corresponds to the opal cements in the soil, averages nearly 5% by weight through a profile more than 1 m thick. Soil processes for accumulating silica are commonly reported (e.g. Langford-Smith, ed., 1978); for the Yucca Mountain deposits, the rates and mechanisms for pedogenic accumulation deserve further examination, but there is no compelling reason to suspect these processes do not occur or are insignificant. We note that uranium series ages from opal from fractures in cores are all interpreted as exceeding 400 ka (Szabo and Kyser, 1990). The age and period of accumulation for silica deposits are less well constrained than for carbonate, and rates of accumulation have not so far become a point of contention.

Hydrothermal sources of silica are also possible, as proposed by Szymanski. For the surficial deposits, oxygen isotope data permit a temperature range which can overlap with low temperature hydrothermal regimes. Silica saturation is relatively low at these temperatures (see Williams and others, 1985a,b) for either surficial processes or for hydrothermal processes unless pH is quite altered (e.g., alkaline soil conditions common in arid environments) or some organic acids are involved, as in pedogenic processes. At present, there are no indicators of high temperatures which would be consistent with rapidly upwelling hydrothermal fluids.

5.5.5 Hydrothermal Alteration Rims

Fractured volcanic rocks and clasts in the Solitario Canyon area (e.g., around the area of borehole WT-7) commonly develop a color band a few mm inside the surface.

During discussions, Szymanski has suggested that this color band is due to hydrothermal alteration by fluids discharged from the fault zone. To our knowledge, these rinds have not been investigated to develop evidence for or against this suggestion.

The panel visited an area in the vicinity of site 106, near the south end of Yucca Mountain, where reddened unwelded tuffs are exposed in an arroyo and are abutted by carbonate-cemented gravel and cobbles. The contact area between unwelded tuff and gravels is more or less planar, though short, and Szymanski believes it is a fault zone along which hydrothermal fluids have welled up, altered the tuff, and produced the carbonate cement. In the field, we observed clasts of the lightly reddened tuff cemented in the gravels well away from the contact. It seems highly improbable that the supposed alteration and carbonate formed from a single event, as other clasts do not show alteration. In addition, reddening is a common phenomenon that may occur as a consequence of weathering, diagenesis, or hydrothermal alteration. For the moment, we have no attributable information to demonstrate that the reddened zone is controlled either stratigraphically or by the supposed fault plane, or even whether it is old, young, hydrothermal, or not.

The near surface carbonate and silica unit at site 106 appears to us to greatly resemble other deposits attributed to pedogenic processes in the area. Some areas we examined have greater abundance of rhizoliths and physical character which suggest wetter zones or are associated with finer host sediment. The panel majority believes this area requires only the ordinary scrutiny applied to such deposits in the Yucca Mountain area.

5.5.6 Isotopic Data

Szymanski (1989) referred briefly to isotopic data and their bearing on his ideas. In his later draft report to the panel, Szymanski (1990) included various isotopic data and interpreted these data as supporting his concepts and limiting or rejecting other concepts of the hydrogeologic system at Yucca Mountain and the origin of carbonate/silica deposits. Szymanski (1990) referred to stable isotopes, ^{36}Cl, $^{87}Sr/^{86}Sr$, and uranium series. More recent letters by Szymanski refer extensively to geochemical data and arguments, but they are not explicitly reviewed in this report.

1. $^{87}\underline{Sr}/^{86}\underline{Sr}$. The panel majority sees the $^{87}Sr/^{86}Sr$ data as the most permissive or supportive evidence of upwelling fluid which may have circulated to considerable depths beneath the tuffs. The relatively high ratios (about 0.7120 to

0.7130) of strontium isotopes of surficial and vein carbonates at Trench 14 are unlike groundwater (about 0.7100 to 0.7120) so far analyzed from the area of Yucca Mountain (Muhs and others, 1990). Note that four significant decimal figures are used here for these ratios. Old rocks (e.g., Precambrian) tend to develop high $^{87}Sr/^{86}Sr$ ratios; volcanic rocks may also form with high ratios. Waters interacting extensively with such rocks also acquire high ratios. In the Yucca Mountain area, volcanics in the unsaturated zone from about the Prow Pass Member up to the ground surface generally have $^{87}Sr/^{86}Sr$ ranging from about 0.7100 to 0.7200, overlapping the range for the surficial and vein carbonates at Trench 14 (Marshall and others, 1990). These volcanics could also be sources of the high strontium ratios through weathering (Marshall and others, 1991). Eolian dust sources of carbonate in the Yucca Mountain area may show variable $^{87}Sr/^{86}Sr$ ratios because there are Paleozoic or older carbonates with normal marine ratios (about 0.7080 to 0.7100) as well as carbonates with much higher ratios (Marshall and others, 1991). Three eolian silt samples yielded $^{87}Sr/^{86}Sr$ of 0.7117 (rounded), similar to lower ratios for some pedogenic and vein carbonates in the Yucca Mountain area (Marshall and others, 1991). Certainly one possible interpretation of the $^{87}Sr/^{86}Sr$ data is that it indicates deep circulation, but this is neither the only nor the simplest explanation.

There are groundwaters in the area which have strontium ratios similar to the carbonate/silica deposits at Yucca Mountain. Water from springs near Ash Meadows, south of Yucca Mountain, has similar strontium ratios. The springs include Devil's Hole. Yucca Mountain, however, is located within a different groundwater basin from the Ash Meadow system.

Szymanski proposes that the springs at Ash Meadows and their deposits are related to tectonic control of the hydrology (reflecting discharge from the upwelling limb of a convection cell). Through careful sampling and analysis of stable isotopes and radiometric age determinations, Winograd and others (1990) relate stable isotopic changes in the Devil's Hole carbonate deposits to climatic variations during the Pleistocene. The isotopes vary in a way that is consistent with climatic reconstructions elsewhere, but the rate of deposition over about 500,000 years appears more or less constant; there is no evidence of depositional episodes separated by several tens of thousands of years, as proposed by Szymanski for a tectonic cycle which controls the hydrologic system.

2. <u>Oxygen and Carbon Stable Isotopes</u>. The oxygen and carbon stable isotope data from the surficial carbonates at Trench 14, and the vein deposits in the unsaturated

zone, are consistent with an origin tied to fluid infiltration downward from the ground surface. Three points are important in the panel's view: 1) the oxygen and carbon stable isotopes measured in surficial carbonates are strongly suggestive of soil-forming processes (e.g. Cerling, 1984; Quade and others, 1989; Quade and Cerling, 1990), 2) the stable isotope data correspond well with occluded organic carbon within the calcite (Quade and Cerling, 1990), and 3) much of the depth dependent variation in oxygen isotope fractionation, in the limited data that is available, is consistent with waters precipitating carbonate in equilibrium with a geothermal gradient having a value in the range observed at Yucca Mountain (Szabo and Kyser, 1985, 1990) (discussed above). Extraordinary conditions seem necessary to relate these deposits through stable isotopes to processes proposed by Szymanski. Szymanski has proposed that the upwelling fluids which contributed to these deposits had their isotopic characteristics altered by surficial processes while flowing across the ground surface, and therefore the Trench 14 and Busted Butte carbonates do not represent pristine hydrothermal deposits.

It is important to note that the $\delta\ ^{18}O$ values of modern groundwaters from the saturated zone in the vicinity of Yucca Mountain are too low to serve as sources for these carbonates; either the source fluids for upwelling must be more enriched in ^{18}O than present groundwater, or some mechanism, such as evaporation within the upwelling zone, must be proposed to enrich the fluid. As they precipitate, carbonate minerals deplete the fluid in ^{18}O; as a consequence, a mineral sequence precipitated from an upwelling fluid should show lighter $\delta\ ^{18}O$ values upward. In fact, the opposite pattern is observed at Yucca Mountain.

3. <u>Uranium Isotopes</u>. Uranium systematics have been used extensively to examine ages of various deposits as well as to try to rule out potential sources of water for surficial carbonate/silica deposits and vein fillings in Trench 14. Low $^{234}U/^{238}U$ ratios in these deposits are interpreted to require fluid sources with similar low ratios. Waters from boreholes in the vicinity of Yucca Mountain (Muhs and others, 1990) do not yield similarly low ratios, which is interpreted by some as evidence that these groundwaters could not be sources for the deposits.

Szymanski has cited low uranium ratios from groundwater sampled in a broader area around Yucca Mountain as evidence that groundwater can be a source for these carbonate/silica deposits. He emphasizes that uranium values in groundwater are heterogeneous in the area, and that the analyses from Yucca Mountain should not rule

out groundwater sources. As with the strontium data, Szymanski argues that the discordance in the uranium systematics reflects temporal variations in the source areas for the fluids, so that present-day water in the tuffs is not representative of upwelling fluids.

Szymanski (1989, Pl. 4.3.3-50) shows, however, what he considers are thermal anomalies, plotted at a uniform depth of 500 m below the surface, associated with hydrothermal circulation. These are located along the Solitario Canyon and Paintbrush faults. It would seem that groundwater in these areas should yield uranium ratios similar to the deposits alleged to have formed by this process. To date, groundwater from boreholes located along these apparent thermal anomalies do not yield low uranium ratios.

Szymanski (1990) has argued that deep hydrothermal circulation systems will generate low uranium ratios in the fluid similar to ratios of the surficial deposits. The proposal is not well enough developed for us to evaluate it critically.

Another unevaluated (or at least possible) source of water with low uranium ratios could be surficial or near-surface water. Osmund (1980) states that soil water in contact with weathering rock in arid environments can have low uranium ratios. It seems practical to test this hypothesis for the Yucca Mountain area.

Various deposits of carbonate/silica in veins and calcretes have been analyzed, and isotopic ages have been calculated based on uranium systematics. The isotopic age for many deposits provides only a preliminary idea of the time of formation as the accumulation may have been lengthy and sampling not very precise. Whelan and Stuckless (1990) report samples from Trench 14 have ages from 100,000 years to more than 400,000 years old. These dates may suggest episodic deposition, and perhaps faulting. In contrast, for vein fillings at Devil's Hole, it has been possible to use isotopic dates to demonstrate apparently continuous precipitation (e.g., Ludwig and others, 1990). Single, massive deposition of carbonate and silica can be rejected in these cases.

The radiometric ages for the Yucca Mountain area cannot be used to differentiate episodic from continuous deposition, though macroscopic relationships show at least some disruption of deposition. It would be helpful if some surficial and near surface deposits were carefully sampled to determine more closely the length of time for accumulation of these deposits. These data would provide more control on geomorphic and tectonic stability as well as rates of accumulation. We recognize the isotopic ages will not generally provide a test of Szymanski's ideas, as he believes they may accumulate either slowly or in short episodes.

5.5.7 Other Remarks

In general, Szymanski has proposed intermittent fluid flow not now occurring at Yucca Mountain, and postulated fluid sources, beyond current drilling, to provide fluid sources with appropriate isotopic characteristics to form the surficial carbonate/silica deposits. We would oppose deep drilling as a means of testing Szymanski's geochemical ideas as he has not provided the basis for specific test objectives.

It is appropriate to continue to investigate the evidence for water table changes through geologic time in the general area of Yucca Mountain. A number of features are not yet understood with adequate certainty. For example, uranium ratios and content are more variable in core samples than in the surficial deposits. The USGS has recently proposed that a location called site 199, at the south end of Crater Flat, should be investigated as a likely spring deposit formed well above the present water table. Careful analyses will be required to establish whether these deposits reflect water table positions, and if so, whether the deposits show relative uplift, local spring deposits, perched water tables, hydrothermal circulation, seismic pumping, or some combination. However, as long as criteria are unspecified for differentiating among these processes, each favored idea could continue to be revised arbitrarily to account for new observations without obtaining any resolution.

This discussion does not resolve or address in any detail the significance of carbonate/silica-filled fractures at depth in the unsaturated zone at Yucca Mountain. There are few data; they suggest that thermal gradients may have been higher more than 400,000 years ago. There are indications that these fracture fillings are distributed in zones. Deeper fillings mostly appear older than are shallower fillings. Hydrologic conditions leading to the formation of the vein-filling carbonates, should they originate from the infiltration of meteoric water, are apparently not well-understood. The role, if any, of transient zones of perched water occurring above the main water table would need to be clarified. The mechanisms and effects of fluid flow, solute transfer, and vapor transport in the unsaturated fractured rocks at Yucca Mountain and their effects on mineral precipitation are uncertain. Recurrence intervals, should the conditions leading to vein formation be episodic, are not constrained by the existing data base. In spite of the significance of the history of the present-day unsaturated zone, available information has not been synthesized in any ready form we have seen.

It is important to provide a firm basis for delineating the extent and nature of these fracture fillings within cores, and then examine their origin. It is particularly noteworthy that many of the geochemical analyses were completed some time ago, and that methods of analysis have improved since then. In addition, the sampling was limited and not intended to address the questions now being asked. As a consequence, we are concerned that the present data are of limited use in deducing the history of hydrologic changes within the unsaturated zone.

5.6 Summary of Important Hydrological Information

5.6.1 General Comments

The basic and important facts about the current hydrological information are the configuration of the water table and the fracture permeability. Some of the geological evidence previously discussed has been interpreted by Szymanski to demonstrate an earlier, higher water table produced by tectonic processes. From this interpretation, Szymanski also expects the proposed repository zone to be eventually saturated by upwelling fluids. Here we will examine the evidence and interpretations in that order. We do not discuss Szymanski's interpretation of hydraulic mounds and perched water. We have reviewed the careful and detailed analysis in the internal review document (Dudley and others, 1989), and we are in basic agreement with the conclusions reached there concerning this topic. The hydraulic, thermal, and chemical data do not provide any clear evidence that favors a tectonic origin over an origin explainable in terms of a perched water body or a groundwater mound originating from meteoric recharge.

The major characteristics of the water table are known and not in dispute. Under much of the southern part of Yucca Mountain and the proposed repository zone, the water table is at an elevation of about 730 m. It rises relatively steeply northward to elevations of about 1030 m at USW G-2. The gradient is to the south, southeast, and east, in general toward Forty Mile Wash, in the Yucca Mountain area. The area of steeper gradient has attracted much attention. The character of the gradient is not constrained in the north. Three general explanations are available: a) significantly larger permeabilities in the southern area than in the north, b) a permeability structure in the area of steeper gradient, or c) differing underlying units draining these respective areas.

We do not infer, as Szymanski (1989; p. 4-13) has done, that it follows from the "indiscriminant occurrences of highly variable lateral gradients in hydraulic potential, that in the Death Valley groundwater system, the hydraulic conductivity structure lacks continuity and lithostratigraphic consistency". It is entirely reasonable to anticipate such gradients in mountainous terrain, in an area with a complex, three dimensional hydrostratigraphic setting typical of the Nevada Test Site.

Szymanski explains the region of the steep gradient on the water table in terms of a changing state of stress and its control on fracture permeability. Thus, the southern part of the area is in later stages of extension in his tectonic cycle, leading to greater permeability and porosity and lowering the water table. The northern part of the area has not yet been affected by the tectonic cycle; it is in an early stage of the tectonic cycle with diminished fracture permeability. The water table would remain high in this area until extension began to change the permeability.

5.6.2 Hydraulic Conductivity

Szymanski believes that the hydraulic conductivity of the tuffs is determined by the *in situ* distribution of stress, independent of the lithostratigraphic framework. We agree that the field-scale hydraulic properties of the tuffs and carbonate rocks, in the saturated zone, are controlled by the nature and properties of fractures. The panel rejects the concept that hydraulic conductivity is solely a function of fracture aperture. Nor do we agree with the concept that if the tuffs are found to have a high permeability, then the rock mass must be in an advanced state of dilation. Higher fracture densities, better interconnections of fractures, greater frequencies of open channels within fracture planes, and larger residual apertures are all factors that must be considered in interpreting hydraulic conductivity measurements.

With the premise that the local value of the *in situ* stress is the only significant factor determining the magnitude of hydraulic conductivity, Szymanski characterizes the Death Valley groundwater system in terms of two units, alluvium and all underlying rock units. Sufficient weight of evidence argues for at least five hydrostratigraphic units as the foundation of any conceptual model (alluvium, Tertiary volcanics of higher and lower permeability, Paleozoic sedimentary rocks of higher and lower permeability). The underlying Precambrian rocks could be viewed as a sixth hydrostratigraphic unit, although we know little about that unit.

The manner in which the data are presented (Szymanski, 1989; Pl 4.2.2-1) is insufficient to claim that within the tuffs, there is no discernable relationship between matrix permeability and lithology. Others have analyzed the same data and concluded that there is a difference in matrix permeabilities for the welded and nonwelded tuffs (e.g., Peters and others, 1984). Matrix permeabilities are heterogeneous and, in some units values appear to vary to a greater degree than in others. Comparisons must be based on a statistical analysis of the measurements, tied to lithologic descriptions, and not just on a comparison of the range of values observed. From Pl. 4.2.2-1 and 4.2.2-2, Szymanski concludes that matrix permeabilities for the entire section appear reasonably homogeneous.

The permeability of the carbonate unit is very heterogeneous; high permeability is reported to be restricted to isolated zones of apparently more concentrated fracturing (e.g., Winograd and Thordarson, 1975). Szymanski explains the presence of higher permeability zones in the carbonate aquifer (below the surface Z) in terms of a higher residual aperture than the value of residual aperture for the overlying tuffs. As a consequence, rock units below the Z surface may still exhibit a permeability contrast. By invoking this assumption, high permeabilities in the carbonate aquifer are eliminated as a possible counterexample to Szymanski's concept that the *in situ* stress distribution determines the permeability structure, and not the lithostratigraphy. No data are presented by Szymanski to support the statement that the permeable carbonate zones can be attributed to a higher residual aperture.

On the basis of comparing estimates of transmissivity for both the carbonates and tuffs, Szymanski suggests that the data do not support the idea that the carbonate rocks are the most transmissive parts of the groundwater system. He also draws the conclusion from this comparison that fracture permeability may be independent of lithologic character. The data given in Pl 4.2.2-3 through 4.2.2-5 do not provide substantive support for this conclusion. The panel majority agrees that locally, units classified as aquifers within the tuffs may be as permeable as transmissive sections of the carbonate aquifer. The data given in these plates, although limited in number, support this statement. Nevertheless, the areal extent, connectivity, relative abundance of permeable horizons, and the disposition of lower-permeability aquitards must be addressed to draw the more general conclusion made by Szymanski. His report does not address these issues.

Szymanski claims he can recognize three layers in the hydraulic conductivity structure (see Pl. 4.2.2-13, 4.2.2-14). The boundaries separating these three layers are not colinear with either stratigraphic boundaries, nor with lines of equal overburden stress. From this interpretation, Szymanski concludes lithostratigraphic factors which control the density of fracturing are not responsible for the observed distribution of hydraulic conductivity. The panel majority believes that the identification of a three-layer structure in the hydraulic conductivity data set is tenuous at best. Thus, we give little weight to interpretations derived from Szymanski's analysis of this data.

The following comments about these figures from Szymanski (1989) are in order:

Plate 4.2.2-13 (East-West Cross Section)

USW H-6. Two injection tests at the bottom of this hole yield hydraulic conductivity values that are lower than any measurements higher up in the section. It could be inferred that permeabilities at depth are approaching matrix values. This is not a strong test, however, and the data could equally well be interpreted as a local zone of low fracture permeability.

USW H-3. Except with respect to the shallowest measurement, there is no apparent trend to reduced permeability with depth.

USW H-4. Higher-permeability tuffs occur throughout the depth range of measurement. This region appears to be more permeable than elsewhere along the section.

UE-25p#1. Tuffs are moderately permeable here (10^{-3} to 10^{-2} m/day) and overlies carbonates with higher hydraulic conductivity (10^{-2} to 10^{-1} m/day).

Plate 4.2.2-14 (Southwest-Northwest Section)

USW H-1. These data suggest that below the uppermost 200 meters of the saturated zone, permeability is low and approaches values corresponding to matrix permeability.

UE-25b#1. One measurement at the bottom of the hole yields a permeability estimate approaching matrix values.

The data suggest to the panel that to the northwest, hydraulic conductivity of the tuffs at depth is relatively low. In the vicinity of UE-25p#1, it is relatively high.

The few measurements in the carbonate aquifer show it to have high hydraulic conductivity. The tuffs are locally as permeable as the carbonate unit. It is difficult to support any spatial pattern beyond this, given the data base and the quality of the measurements. The data on these two figures (Pl. 4.2.2-13 and 4.2.2-14) do not provide substantial evidence for the presence of a surface Z(x,y,t), above which permeability is enhanced by fracture dilatancy. Thus, the available data do not demonstrate, as claimed by Szymanski, that the spatial variability in hydraulic conductivity is consistent with his model of a deforming fractured medium.

Bish and Vaniman (1985) describe patterns of mineral alteration which may be related to permeability differences. At well G-2, glass is abundant in stratigraphic zones at the base of the Topopah Springs Member above the water table. Densely welded vitrophyre survives nearer the water table in the north, but the underlying non-welded vitric zone is not present near the water table at G-2. Instead, clay (smectite) and zeolites (clinoptilolite/mordenite) are more abundant. These minerals are common alteration products of glass, and they minerals are likely contributors to the hydraulic conductivity contrasts in the units shown by Szymanski (e.g.. pl 4.2.2-13).

Glass existing in nonwelded zones in the interval between the water table and repository zone are evidence consistent with a history of being unsaturated. This does not prove the zone has always been unsaturated, as glass exists even now, though in limited occurrences in rocks of apparent lower permeability, below the water table at Yucca Mountain.

5.6.3 Water Level Hydrographs

Szymanski (1989; sec. 4.1) states that the water level data being collected at Yucca Mountain provide an important test for his conceptual model. As discussed earlier in our report, he expects to see two characteristics: a long-term decline in water levels due to continuing extension and short-term fluctuations in water levels due to spontaneous restructuring of the *in situ* stress above the surface Z. These latter fluctuations may involve "several meters, perhaps tens of meters displacement of the water table, and last for days to weeks at most."

Szymanski suggests that a number of hydrographs for the water table wells (Plates 4.2.4.4-6 through 4.2.4.4-16) indicate a small progressive decay in water level during 1984. On this basis, those wells are important in defining the presence and spatial

extent of the region designated by Szymanski as Zone I. In reviewing the water level hydrographs for 10 wells located downgradient of the region with the steep slope on the water table (Gemmell, 1990), the panel sees no evidence in that data to suggest a longer-term decline in water levels. This observation applies to both the average water level elevation for the six-year period 1983-1988 and the more detailed hydrographs showing water level fluctuations in the periodically measured wells during 1987 and 1988. Visual inspection shows both water level increases and decreases are observed about an average value that apparently changes little over the period of record. In terms of conventional hydrogeologic models, there is no evidence of anomalous or unexpected behavior. A similar conclusion is reached upon examining all the available hydrographs for the period 1981 - 1987, published by Robinson and others (1988). In several of the hydrographs (e.g. USW WT-1), water level changes exceeding 0.2 m are observed. It is suggested in that report that these fluctuations are readily explainable in terms of changes in measurement equipment.

The panel majority members point out a concern with the water level data presented in Szymanski's 1989 report. Although reference is made to the report by Robinson and others (1988), which includes the water level data through 1987, Szymanski only includes data for 1984 and 1985. Since he attaches such importance to the water level data, it is reasonable to have expected a presentation of all the data that were available in his 1989 revision.

Three panel members (Archambeau, Rudnicki, Smith) were given a brief, informal overview of the continuous water level data (USGS draft report, in review). Jerry Szymanski expects significant, short-term fluctuations in water levels within a deforming fractured medium in an advanced state of dilation, as "singular points" migrate with stress readjustments. Long-term, continuous water level measurements in deep boreholes push the limits of hydrogeologic practice. Interpretation of this data is confounded by problems with transducer drift, failure, and/or malfunction. There are interesting responses in the hourly transducer records for a number of monitoring wells, during time intervals when the transducers were apparently functioning in a normal manner. It is the panel's understanding that the nature and possible cause of the fluctuations in transducer response remain an open question. One possibility is that it is a hydraulic response to micro-strain readjustments within the tuffs. Further examination of this data is required, a point clearly recognized by USGS personnel responsible for the water level monitoring program at Yucca Mountain.

6.0 RECOMMENDATIONS FOR DATA COLLECTION AND/OR ANALYSIS

6.1 General

Although the panel majority has concluded that Szymanski's conceptual model warrants no special consideration during site characterization, we believe there are issues related to possible influence of the tectonic setting on the hydrologic system at Yucca Mountain that merit attention. The recommendations for data collection and/or analysis, if implemented, could contribute to a better understanding of these issues. The full panel developed some initial recommendations which are partially to wholly incorporated or modified by the panel majority here.

Recommendations by the panel majority are grouped into three categories:

A - recommendations assigned higher priority

B - recommendations related to the resolution of important issues

C - recommendations leading to longer-term improvement in the understanding of how the tectonic setting at Yucca Mountain may influence the hydrologic system.

6.2 A: Recommendations Assigned Higher Priority

1) Integrate information on vein/fracture filling; including the character, relative abundance with depth, volume, chemistry, age, and other mineralogical information bearing on the hydrogeological history of the present-day unsaturated zone at Yucca Mountain. Age and spatial relationships must be analyzed. This task of reconstructing the hydrogeological history of the present-day unsaturated zone should be initiated as soon as possible using data now available or soon to be released. The report should examine whether existing age estimates for calcite precipitates are of sufficient reliability to be used for this purpose. This history should be revised periodically during site characterization to reflect new data and understanding.

2) Based on the integrated information on the unsaturated zone, further analyze the age, chemistry, and temperature of formation of the veins, to understand the mechanisms which formed veins within the full extent of the present-day unsaturated zone. New samples will need to be collected specifically for this purpose. Recent

advances in the analysis of small samples (e.g. for uranium series dating) improve the prospects for delineating the sources and determining the ages of calcite veins and other secondary minerals in the unsaturated zone.

3) Extend Trench 14 at shallow depths to the top of the ridge to the east. The purpose of the extension is to confirm the absence or presence of a fluid source that Szymanski requires if the Trench 14 deposits are to be attributed to upwelling fluids. This fluid source must show a thermal anomaly and stable isotope geochemistry not affected by biogenic activity if it is to provide support for Szymanski's claim of upwelling fluids.

6.3 B: Recommendations Related to the Resolution of Important Issues

1) The steep water table gradient is an important feature of the hydrologic system at Yucca Mountain. Priority should be given to determining the factors that give rise to the steep gradient. Different project studies that could bear on this issue must be coordinated. Several hypotheses have been proposed to explain the origin and positioning of the steep gradient, and analyses should proceed along lines that allow these hypotheses to be specifically evaluated.

2) A surface strain monitoring network should be established at Yucca Mountain. In addition, at least one borehole strain meter should be installed, ideally in the vicinity of a continuously monitored water well. The borehole data should permit correlation of strain measurements with fluid pressure fluctuations.

3) Obtain additional measurements of *in situ* stress in existing boreholes, emphasizing boreholes located downgradient, across, and upgradient of the region at Yucca Mountain with the steep slope on the water table. The purpose of these measurments is to investigate possible relationships between *in situ* stress and hydraulic properties of the tuffs; the stress measurements should be coordinated with hydraulic testing programs.

4) Investigate possible oscillations of water level in continuously monitored boreholes with a short-term program: i) to resolve the character and origin of

anomalous water level data, and ii) to determine the extent of water level changes in the fractured tuffs to seismic loading and possible small scale strain readjustments. The anomalous water level data refers to short-lived fluctuations in transducer response occasionally observed in some continuously monitored boreholes at Yucca Mountain. Monitoring should emphasize the response of confined aquifer zones.

5) Future hydraulic tests to characterize the rock mass below the water table at Yucca Mountain should be carried out over shorter borehole intervals than has previously been the case. This approach provides more reliable estimates of hydrogeologic properties and permits a more direct correlation with lithology and fracture characteristics. We do not recommend slug tests be carried out unless much smaller applied hydraulic heads can be used than has been common in the past.

6) Model studies should be continued to refine estimates of the magnitude and spatial extent of fluid pressure perturbations and water table rise due to strain release associated with seismic rupture.

7) A better understanding of the effects of thermal events in the region of Yucca Mountain on the hydrologic and geochemical systems is required. The magnitude of a water table rise due to the onset of hydrothermal convection should be evaluated. This evaluation should be carried out within the framework of the regional topographically-driven groundwater flow. These model studies should focus on the geologic setting at Yucca Mountain.

8) Several boreholes at Yucca Mountain should be designed specifically to obtain accurate subsurface temperature measurements. The objective is to eliminate any thermal disturbance attributable to fluid flow along the axis of the borehole. Borehole temperature measurements will be important in resolving uncertainties in the current understanding of the thermal regime. The temperature-depth measurements should also contribute to better definition of groundwater flow patterns and flow rates. These boreholes ideally would extend into the carbonate aquifer, and perhaps some distance below it.

9) Develop objective summaries of site suitability topics, similar to the recommended summary of the history of the unsaturated zone, useful to both investigators and managers. These documents will be helpful in summarizing information across the boundaries of technical disciplines. The reports should a be new syntheses of technical information from a broader perspective, and they should be revised as necessary to reflect new data and understanding.

10) We note that data are not yet available to adequately characterize rates of deposition of the surface-parallel calcite/silica deposits. Detailed isotopic sampling (dating) along appropriately-oriented profiles and continued evaluation of sources of calcite and silica (e.g., eolian, leaching from volcanic rocks) are required to further test hypotheses related to pedogenic origins of these deposits.

6.4 C: Longer-Term Improvement in Understanding

1) Examine the possibility of the occurrence of low-velocity zones in the crust in the vicinity of Yucca Mountain with high-resolution seismic tomography, indicating the presence of partial melt. This data could be used to evaluate the potential for increasing heat flow through geologic time in the vicinity of Yucca Mountain. This project would refine earlier work by Montfort and Evans (1982).

2) A study should be carried out to determine to what extent large wall rock separations, if such exist, are a characteristic feature of fault zones within the Basin and Range and to elucidate the mechanisms of their occurrence.

3) The potential for long-term changes in the hydraulic properties of the tuffs and fault zones, and how those changes may affect the suitability of the site to host a repository, needs to be evaluated. For example, tectonic extension over the time period of regulatory concern may alter permeability to the extent that additional uncertainty is introduced into evaluations based on present-day rates of fluid flow in the saturated zone.

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APPENDIX: On the Development of Excess Pressure at Depth Due to Lowering of the Water Table

An element of Szymanski's model is the development of "overpressures" at depth due to lowering of the water table (Section 3.3.4 and elsewhere). By "overpressure" he evidently means that the pressure at depth exceeds that which is consistent with the lowered position of the water table; in other words, the pore fluid at depth has not had sufficient time to adjust to the new position of the water table. This is not the conventional usage of the term "overpressure" and the effect will be termed disequilibrium pressure here. The analysis here and reasonable estimates of the hydraulic diffusivity, seismic inter-event time and magnitude of the water table decline indicate that significant disequilibrium pressures due to a declining water table are unlikely to develop.

Szymanski discusses neither the rate at which the process proceeds nor the expected duration of the disequilibrium pressures. These pressures can be generated by a declining water table only if the water table falls faster than the diffusion of pore fluid can equilibrate the difference in pressures. In this section, an estimate is made of the time scales of water table lowering (which is presumably related to the rate of tectonic straining) and of pore fluid diffusion, and the effects of these time scales on the existence, depth and duration of the hypothesized disequilibrium pressure.

The perturbation in the pressure caused by lowering of the water table is governed by the diffusion equation:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c}\frac{\partial p}{\partial t} \tag{A.1}$$

assuming one dimensional diffusion in depth and a constant diffusivity c. Thus, effects of lateral flow and non-uniformity in the vertical permeability are neglected. In a heterogeneous geologic setting, two and three dimensional flow will allow more rapid equilibration of the pressure. Thus, the one dimensional calculation provides an upper bound on the magnitude and duration of the disequilibrium pressure.

Suppose the water table is lowered from a depth z_1 to a depth z_2, where $\Delta h = z_2 - z_1$ (Figure 1). Then, the pore pressure at depth z_2 decreases by an amount P_0 ($= \rho g \Delta h$, where ρ is the density of water and g is the gravitational acceleration). For simplicity, assume the pressure decrease occurs as a linear ramp function:

$$p(x=0,\ t) = -P_0 t/T, \quad 0 < t < T$$

$$p(x=0,\ t) = -P_0, \quad t \geq T. \tag{A.2}$$

where $x = 0$ is the new (lowered) position of the water table. The initial condition is

$$p(x,\ t=0) = 0 \tag{A.3}$$

The alteration in pore pressure below the new position of the water table is given by the solution of (A.1) subject to (A.2) and (A.3):

$$p(x,t) = -P_0\left\{H(t)\ (t/T)\ I[x/\sqrt{4ct}] - H(t-T)\ [(t/T)-1]\ I[x/\sqrt{4c(t-T)}]\right\} \tag{A.4}$$

where H(t) is the unit step function,

$$I(\xi) = erfc(\xi) - (2/\sqrt{\pi})\ \xi\ \exp(-\xi^2) + 2\xi^2 erfc(\xi), \tag{A.5}$$

and $erfc(\xi)$ is the complementary error function.

In order to interpret this solution, it is useful to introduce a nondimensional depth $X = x/\Delta h$ and a nondimensional time $\tau = t/T$. A consequence of this choice is the appearance of the following nondimensional parameter:

$$\beta = \frac{\Delta h}{\sqrt{4cT}} = \frac{(\Delta h/T)}{\sqrt{(4c/T)}} \tag{A.6}$$

The first form is the ratio of the water table drop Δh to the characteristic length of diffusion for the time period of water table lowering $(4cT)^{1/2}$. The second form expresses β in terms of rates: the ratio of the rate at which the water table is falling to a characteristic velocity of pore fluid diffusion.

The effect of the parameter β can be understood by examining plots of the normalized disequilibrium pressure $P(x,t)$, which is given by

$$P(x,t) = 1 + p(x,t)/P_0 \tag{A.7}$$

Figure 2 shows the disequilibrium pressure as a function of the nondimensional depth $X=x/\Delta h$ (below the current water table) at the time the water table has been lowered to its new position ($t=T$) for the following values of β: 0.01, 0.05, 0.1, 0.5, 1.0. For $\beta=1$, the disequilibrium pressure exceeds 90% of its maximum value (P_0) at depths

greater than Δh below the current position of the water table. For $\beta = 0.01$, the disequilibrium pressure is less than about 10% of the maximum value at depths less than $5\Delta h$ below the current water table.

An alternative way to interpret the solution is to consider the duration of the disequilibrium pressure at a given depth below the new water table. Figure 3 shows the disequilibrium pressure at $X = 1$, a depth Δh below the current water table, as a function of the time t/T for several values of β. For $\beta = 1.0$, the disequilibrium pressure is about 0.75 P_0 at $t = T$. For $\beta = 0.1$, the disequilibrium pressure is only about 0.2 P_0 at $t = T$ and falls to about 0.1 P_0 at $t = 2T$.

Obviously, the magnitude and duration of the disequilibrium pressure predicted by the solution depends on the value of the nondimensional combination $\beta = \Delta h/(4cT)^{1/2}$ and, hence, on values for the water table drop Δh, the hydraulic diffusivity c and the time scale of the drop T. The examples presented in Figures 2 and 3 suggest that development of a disequilibrium pressure of significant magnitude and duration requires values of β near unity and certainly greater than 0.05. Although the values of the parameters entering β are not known with certainty, plausible estimates consistent with Syzmanski's concept suggest values of β much less than 0.05.

If the water table at Yucca Mountain reached the surface at some time in the past, as proposed by Szymanski, the current position at about 500 m below the surface corresponds to a drop of 0.5 km. In addition, Szymanski's interpretation of the steep water table gradient at the north end of Yucca Mountain as separating domains that are early and late in the stress cycle implies a value of Δh of about 300 m. Hence, a value of Δh of about 1 km seems to be an upper bound on the water table drop implied by Szymanski's concept.

Because Szymanski proposes that the lowering of the water table is a cyclic process that is restarted by the occurrence of an earthquake, it is reasonable to assume that the time scale of the water table lowering is of the order of the inter-event time for earthquakes. Values of about 10^3 to 10^4 years have been suggested for the vicinity of Yucca Mountain. The lower value is consistent with a strain-rate of 10^{-7} per year, which may be appropriate for the Basin and Range, and a characteristic earthquake strain of 10^{-4}; that is, the ratio of slip to slip length is usually about 10^{-4} [Kanamori and Anderson, 1975]. Values greater than 10^4 years may be possible for this tectonic setting but values much less than 10^3 years seem unlikely.

Rudnicki [1984] has summarized values of the diffusivity c representative of field conditions near faults

These range from 0.01 to 10.0 m^2/s with values of 0.1 to 1.0 m^2/s as most typical [Roeloffs and Rudnicki, 1984/85]. Values of 0.1 to 1.0 m^2/s correspond to hydraulic conductivities at the lower end of the range determined by pumping tests for the tuff "pile" at the Nevada Test Site and vicinity (Szymanski, Plate 4.2.2-4). In addition, Galloway and Rojstaczer [1988] have inferred a value of about 0.3 m^2/s, which is consistent with this range, from the analysis of the response of wells at Yucca Mountain to earth tides and atmospheric loading. Values inferred from tests on laboratory size specimens are typically much lower, say, 10^{-4} m^2/s (1 cm^2/s) [Rice and Cleary, 1976]. This disparity between in-situ and laboratory measurements is commonly observed and largely reflects the influence of fracturing within the rock mass on the hydraulic properties.

For Δh = 1 km, $T = 10^3$ to 10^4 years and c = 0.1 to 1.0 m^2/s, β ranges from 8.9 x 10^{-4} to 8.9 x 10^{-5}. According to the calculations above, these values are far too small to result in any significant disequilibrium pressure. Even increasing Δh by a factor of 5 and decreasing T by a factor of 10, alterations which strain the range of plausible values, result in values of β that are still too small. An upper bound on β of 0.28 is obtained by using a laboratory scale value for diffusivity, $c = 10^{-4} m^2/s$ and $T = 10^3$ years. Although this value is within the range for which significant disequilibrium pressure will be generated, the diffusivity is far below that representative of field conditions near faults. Thus, fluid pressures generated by a water table decline on the time scale of the seismic interevent time are likely to equilibrate relatively rapidly.

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APPENDIX B

GENERAL LISTING OF ACTIVITIES

EXTERNAL REVIEW PANEL

Late 1989	Prospective panel members contacted
January, 1990	Panel members selected: Charles Archambeau, Dennis Powers, Neville Price, John Rudnicki, Leslie Smith. DOE requests Dennis Powers chair panel.
February 19-21	Neville Price in field with J. Szymanski, G. Frazier.
February 22-23	Panel meets initially in Las Vegas; field trip to Yucca Mt area with J. Szymanski, USGS and DOE personnel.
February 24-26	Dennis Powers in field in Death Valley area.
March	Neville Price forwards draft comments to panel.
April 5-6	Panel meets in Boulder, CO; Szymanski, Frazier, Dudley available for consultation, comments; Szymanski makes draft document on geochemistry available.
April 26	Dennis Powers discusses some impressions of draft geochemistry document with Jerry Szymanski.
April 27-28	Leslie Smith and Dennis Powers to Yucca Mountain area with Jerry Szymanski.
May	John Rudnicki comments distributed to panel. Neville Price second set of comments to panel. Dennis Powers comments on draft document on geochemistry to panel and J. Szymanski. Leslie Smith comments to panel.
June 4-7	Panel meets in Las Vegas; presentations, discussions by J. Szymanski, T. Cerling, D. Muhs, Z. Peterman, J. Healey, G. Frazier.
June	Revision of May comments by Leslie Smith to panel.
June 8	Powers, Price, Smith continue discussion of processes; DOE presents overview of SCP.
June 8-10	Charles Archambeau to Yucca Mountain area with Jack Healey, J. Szymanski, G. Frazier.
June 16-17	Panel meets in Boulder, CO; summarizes key processes.
June	Draft comments by Leslie Smith on summary of key processes to panel for review.
June 26-27	John Rudnicki and Dennis Powers to Yucca Mountain area with G. Frazier.
July	Draft comments by Leslie Smith on SCP Postclosure Tectonics to panel.
July 30	Dennis Powers meets with USGS personnel in Denver re geochemistry/hydrology studies.
July 31-Aug 3	Panel meets in Boulder, CO, to draft consensus and report; Archambeau, Rudnicki, Smith meet with USGS in Denver to review continuous water level data.

October	Dennis Powers participates in field trip to Yucca Mountain and area conducted for NAS Panel on Coupled Processes.
November	Charles Archambeau in field with Szymanski and Frazier.
December 15-17	Panel in field with J. Szymanski; reviews draft and determines form and content of final report.
January, 1991	Charles Archambeau to field with makeup field trip for NAS Panel to Yucca Mountain.
July, 1991	Panel majority meets in Las Vegas to revise draft; field trips to sites 106, 199, and deepened Trench 14.
August, 1991	Panel majority releases final report.

APPENDIX C
DOCUMENTS REVIEWED BY PANEL MEMBERS

Szymanski, J., 1989, Conceptual considerations of the Yucca Mountain groundwater system with special emphasis on the adequacy of this system to accommodate a high-level nuclear waste repository: unpublished report to Department of Energy, Yucca Mountain Project, v. I-III, dated July 26, 1989.

Szymanski, J., 1990, The Yucca Mountain hydrogenic deposits - an engineering geologist's inquiry into their genesis and potential conceptual importance: draft report, dated May 15.

U.S. Department of Energy, 1988, Site characterization plan: DOE/RW-0199, U.S. Department of Energy, Washington, D.C., v. I-IX, many, many pages.