An Assessment of J.S. Szymanski's Conceptual Hydro-Tectonic Model and Its Relevance to Hydrologic and Geologic Processes at the Proposed Yucca Mountain Nuclear Waste Repository

Minority Report of the Special DOE Review Panel

Charles B. Archambeau and Neville J. Price

Charles Archambeau

Dr. C.B. Archambeau
Campus Box 449
Univ. of Colorado
Boulder, CO 80309

Neville J. Price

Dr. N.J. Price
6 Blacks Friars St.
Stamford
Lincolnshire PE9-2BW
United Kingdom

REC'D W/LTR DTD 9112120262 911210 AND
9112120264 911210

Table of Contents

I. Introduction: Objectives and Scope

The main issue in assessing the suitability of a high level nuclear waste repository site is whether the physical environment at the site has the inherent characteristics that would make escape and movement of radionuclides into the biosphere, even in the long term, a highly unlikely event [1]. To quantify this somewhat, by "long term" it is usually stated that 10,000 years is about the time required for containment with a probability of success at better than 95%.

If, as appears to be the case, the repository is used to store young radioactive materials with a high rate of decay, the containment cannisters (spaced 5 meters apart) would reach temperatures above 200° C and the rock between cannisters would reach temperatures well above 100°C and remain so for a long period of time [2,3]. Because of the high temperatures, it seems generally agreed that the most likely and serious problems with containment arise from the possibility of invasion of a repository by water, or a combination of water, steam and, in the extreme, case gas (*ie.* CO_2).

In case of water invasion of a high temperature repository it is likely that corrosion and container break-down would be relatively rapid and that continuing fluid flow could then act to transport any leaked radioactive material, taken into solution, to significant distances within the ground water system. Further, gas and steam flow, when present, could also result in transport directly into the atmosphere.

If fluid and gas intrusion were to occur in association with an earthquake that caused rock faulting within the repository and rupturing of some (but probably few) of the containment cannisters, then exposure of some of the radioactive material to the moving fluid flow could occur very soon after the event. Likewise, occurrence of nearby volcanic activity, with or without significant earthquakes, could also result in rather rapid fluid and gas injection, with similar possibilities for transport of radioactive material out of the repository. Consequently, possible changes in the tectonic and hydrologic environment at or near the repository site are of major concern, for if these changes were properly coupled and of sufficient magnitude, they could result in water and/or gas intrusion in a relatively short time. Considering the thermal state of the repository there would be clear risk for a resulting loss of containment.

It has been pointed out by some scientists [4], in review of the stringent standards for containment, that the required degree of confidence over a period of many thousands of years cannot, in truth, be given. However, the need to give such confident assurances before a high level waste repository can be built could lead those responsible for the preliminary assessment process to practice a form of self delusion, in which the necessary assurances and supporting technical arguments are generated by narrowly focusing on that part of the geologic data and evidence that seems to allow quite conventional interpretations to be made supporting the suitability of the site.

Since even an extensive body of geologic, geochemical and geophysical data can be subject to a lack of unique interpretation, in that more than one theory or conceptual framework can appear viable as a means of explaining the observations, it is certainly possible to focus on the approach that interprets the data in the most favorable light. Given this (probably superficial) lack of uniqueness and a natural inclination to be selective when it comes to interpreting a very large body of uncorrelated information and data, it is not too difficult to produce, at least initially, a description of the geologic environment, including both its history and its probable future, that supports a site as a safe repository. This, of course, does not mean that the interpretation so formed is necessarily incorrect but it does mean that it may be much more uncertain than is apparent to its formulators and that the interpretation could well prove to be incorrect when examined in greater depth and with wider comparisons to field data.

These considerations apply to the current preliminary, generally positive, assessment of the Yucca Mountain geologic environment by the DOE and its contractors, principally the US Geological Survey. However, these pitfalls are also present for any interpretation of the geologic environment at Yucca Mountain, whether it results in a positive or negative assessment of the site as a suitable repository. In this regard, the model described by J.S. Szymanski [5], which attempts to integrate geologic, hydrologic and geochemical information into a framework of interpretation involving the tectonics and hydrology of the Yucca Mountain area, is basically subject to similar uncertainties for the same general reasons that apply to other assessments and models of the site. Thus, while Szymanski's interpretation results in quite a negative assessment of the site's suitability, this fact obviously makes it no less suspect as a framework for interpretation than the alternative interpretations resulting in a much more favorable assessment. In addition, because Szymanski's conceptual framework for prediction and interpretation of the geology is relatively complex and has not yet been studied quantitatively in any detail (partly because the processes involved are strongly non-linear) there is a natural inclination to view his "model" with more than usual scepticism. Certainly there are reasons for such an attitude among scientists, in as much as most have a built-in preference for simple theories and a natural and proper reluctance to subscribe to anything that they do not feel they adequately understand or that has not been adequately tested.

Nevertheless, since the individual mechanisms and physical processes evoked in Szymanski's integrated conceptual model for the behavior of the tectonic and hydrologic environment at the site are all recognized to be possible physical phenomena and could be important (produce large effects) in some circumstances, it is clearly necessary to consider whether they are applicable, in the interactive combinations used in Szymanski's dynamical model, to Yucca Mountain. Therefore, it is the primary objective of this report to evaluate the model that has been proposed by Szymanski as a conceptual framework for interpretation of the observations of the geologic record at Yucca Mountain.

The model explains the presence of numerous calcite-opal veins and extensive surface calcretes at Yucca Mountain in terms of upward water flows, and associated mineral deposition, triggered by interactions between the rapid stress changes following an earthquake and the hydrological state of the medium. Furthermore, it predicts cyclic recurrences of up-welling water, including many in the past and more in the future. In detail the model recognizes that tectonic stresses are a result of an extensional environment at Yucca Mountain. This extension is expected progressively to increase the density and interconnection of open fractures within the upper crust in the area. Thus, slow tectonic deformation is expected to increase the hydrological storage capacity and permeability of the region and lower the water table under conditions of approximately constant water inflow. A long period of extensional deformation of this sort, with gradual lowering of the water table, is expected to end with a large earthquake, or be upset by any renewed volcanic activity, and a rapid readjustment of the distended deformational state of the medium is then expected to occur. This readjustment involves closure of water saturated fractures in many regions and opening of new fractures in others. At this stage, pressure forced flows, that is "seismic pumping", from depth to the surface are expected to be transient, followed by convective flows driven by the high thermal gradients prevailing in the area. These long lasting convective flows, along areas of new and ancient fracturing, are expected to depc a variety of minerals, but principally calcite and opal, in fractures, fault zones and along the surface from the outflows of water along fault zones. This coupled hydrological-tectonic process is expected to be recurrent, that is be repeated with time intervals corresponding to the times between large earthquakes or recurrence periods of volcanic activity.

This model, therefore, is one that would produce episodic, rapid deposition of calcite-opal deposits throughout the mountain and involve large volumes of water and gas injection to near surface depths and even to the surface itself. Because of the recurrent nature of the flow processes and their coupling to the build up and release of tectonic stress, this sequence of processes will be called a "Cyclic Hydro-Tectonic" (CHT) model.

Many, if not most, scientists familiar with the geology and tectonics of the Basin and Range Province, within which Yucca Mountain lies, would probably agree that the general processes just described can conceivably occur. That is, many would agree that, in a strongly extensional tectonic environment at least, some and possibly many fractures in the upper crust could be open (particularly those that are vertically oriented); that changes in the stress field will change fracture apertures (where some may close and some open depending on the details of the stress change); and that these coupled changes in the fractures and tectonic stresses can upset the hydrological stability and produce both rapid pressure-driven flows (seismic pumping) and longer term convective flows. Further, it would likely be agreed that both forms of flow will result in some associated mineral deposition. What is much less generally accepted is the magnitude, spatial extent and duration exhibited by such flows. That is, there is considerable uncertainty as to whether earthquake related tectonic stress changes and associated changes in the fracture controlled permeability and storage capacity are large enough and of a character to produce flow effects involving large volumes of water transported upward to, or very near, the surface of the earth from significant (several kilometer) depths in the upper crust. In this regard, many of the scientists involved in the Yucca Mountain project are clearly doubtful that such strong tectonically initiated effects can occur, either at Yucca Mountain or elsewhere. While most might agree that some level of readjustment in the hydrological environment occurs in response to tectonic activity, they expect it to be transient and of modest to low magnitude with no significant wide spread and long lasting effects. These views appear, however, to be largely based on brief, isolated observations and intuitive expectations rather than solid, site-related evidence or realistic theoretical inference.

There are, however, two obvious approaches that can be followed in assessing whether large magnitude flow effects, involving an upper crust depth range, can occur in response to changes in the tectonic state of the medium. First, one might investigate its plausibility by modeling the complete nonlinear mechanical and hydrological processes using computer based simulations. In this case, one would have to have considerable confidence in the rheological representations adopted, for the solid, including failure criteria, as well as in the approximations to the coupled flow and deformational equations that must be adopted in order to place great weight on the modeling results. Nevertheless, one can certainly explore, by this approach, the range of quantitative flow responses that could be expected using a reasonable range of material conditions and rheologies that spanned the possibilities for the upper crust at the site.

The second approach is fundamental, and that is to evaluate geologic field data from the area to look for evidence of past upward flow and mineral deposition. Broadly speaking, one would expect to see evidence of relatively rapid depositions of minerals in veins and, in some cases, along the surface, with such deposition being episodic and strongly correlated with near vertically oriented fracture zones and faults since the flows are considered to be triggered by relatively infrequent major tectonic events and to be focused in, if not largely confined to, highly fractured or faulted zones. Further, the observed stress field and fracture density, and their orientation in the medium, should be compatible and be such as to indicate fracture controlled permeability and storage capacity. In addition, the mineralization itself should reflect the chemical composition of the water and strata at depth; in the case of Yucca Mountain a major constituent should be calcium from the paleozoic limestones beneath the mountain. Likewise, the isotopic character of the mineral deposits should be compatible with water at considerable depth; or at least compatible with a mixture of the water from greater and shallower depths since the isotopic properties of the water vary with depth.

We should also expect mineral deposition in veins to be observed throughout the depth section above the present water table, as well as on the surface, if major up-welling of water has occurred frequently in the past. Further, the ages of such minerals should span a considerable period, from at least several million of years ago up to essentially the present. In addition, in any restricted area, the ages should be distributed in a reasonably uniform manner if we are to have confidence in the "frequent" occurrence of this up-welling depositional process and its extrapolation to future occurrences.

Finally, one might expect to see evidence of hydrothermal alteration and brecciation of the country rock along faults and in fracture zones, particularly if volcanism has in the recent past been responsible for upward intrusions of water. Again, the ages of any such occurrences would be critical in assessing whether the processes responsible for such high temperature phenomena are still active.

In subsequent sections of this discussion we will explicitly consider field data relative to Szymanski's model in an effort to judge consistency of the model with observations. This evaluation will be in two parts. The first will involve primarily physical geology and hydrology; that is, for example, the compatibility of the Szymanski model predictions with the character and ages of observed faults; the occurrence of mineral deposits at the surface and at depth; and the current stress and fracture state of the system. The second part of the observational evaluation is to compare observed isotopic characteristics of the mineral deposits with those to be expected from this hydro-tectonic model; specifically, whether the isotopic ratios observed for the calcite-opal deposits are consistent with a process involving up-welling of water from considerable depth beneath the mountain. We will also consider the fundamental physical processes involved in the model from a theoretical standpoint, including the likelihood of dilatancy in the upper crust to considerable depth and, ultimately, employ theoretical modeling to assess some of the quantitative characteristics of the flow processes that are expected.

In the following section of this report we define the CHT model as understood by us and describe its features in reasonable detail. We have attempted to represent accurately the original model proposed by Szymanski in his 1989 report. We have also incorporated some elaborations of the model developed since that time, all in order to provide a more complete logical basis for its evaluation relative to observations and modeling studies.

In order that we may better evaluate the CHT model relative to the geologic observations at Yucca Mountain, we consider an alternative model that has been advanced to explain the observations. This model, which we have termed the "Pedogenic Model", is described in Section III. Part of our assessment approach is to contrast the ability of the two different models to provide an explanation of the geologic observations at the site. In terms of plausible models based on our collective knowledge of the geophysical and geologic processes known to be operative, we consider the CHT and "Pedogenic" models to be those that are by far the most likely to be active in the area. Indeed, it is almost certain that both are active to some degree. The question is, is only one of them responsible for most of the calcite-opal veins and surface calcrete deposits at the site, which indicate water depositional processes at work in the past, or are both involved and at what times in the past and to what degree. If the CHT Model fits most or all the observational data, then up-welling water has probably reached the surface from rather great depths and might flood the repository in the future. If the Pedogenic Model provides an explanation for most geologically recent vein and calcrete related data, then it would be much less likely that up-welling water is a problem for repository safety.

Section IV is devoted to the evaluation of critical geologic observations relative to the two model predictions. Here we seek to isolate those geologic features at the site that are most definitive in terms of an assessment of the CHT model. We also consider the compatibility of this field data with pedogenic model predictions in order to explore and evaluate alternative explanations for the origins of these field observations.

Section V is concerned with a review of new material by Szymanski relating to expected geochemical consequences of his model. In particular this section focuses on isotopic characteristics of water deposited minerals at and near the Yucca Mountain site. Here again we find it useful to contrast his model-based explanations of the observed isotopic abundancies with those from the pedogenic model. Our main interest is to judge whether this data can now, or may in the future, provide an unequivocal test of the CHT model or at least an evaluation as to which of the models is best supported by this data.

Of course Szymanski's model is largely qualitative, so that, in the sense of quantitative predictions, its full character is still emerging. Therefore the present assessment is in this respect limited, since we do not systematically and completely explore and assess all of its more quantitative implications. Nevertheless, we do attempt to evaluate some quantitative aspects of the model through analysis of the mechanics of dilatancy and through numerical modeling studies and we discuss the implications of these investigations in sections VI and VII.

These latter sections involve quantitative, physics based, investigations of important aspects of the CHT model. Thus, in Section VI we investigate the conditions under which fracture opening (dilatancy) can occur to rather large depths in a previously heavily faulted area like Yucca Mountain. This arises in our assessment because of the view expressed by some scientists that dilatancy in a faulted medium is unlikely. Thus, while the physical evidence from drill cores as well as pumping and hydrofrature experiments at Yucca Mountain indicate an open fracture system at least to depths of about one kilometer, it is important to determine why this is the case and to what extreme depths one can expect this behavior to occur. Specifically, if the conditions for dilatancy are very special and can occur only in limited zones at shallow depths in rare circumstances, then the possibility that the high volume flow processes following a shallow crustal earthquake will occur at Yucca Mountain are greatly reduced, at least in the form described by Szymanski. However, if regional "on-going" extension and the pre-existing faulting prevailing at Yucca Mountain can be shown to produce upper crustal dilatancy prior to failure along a major fault, then high volume water and gas flows with origins in the upper crust are not only possible but likely.

In this regard, Section VII describes the results of a computer base numerical modeling investigation of some hydrological consequences of a large earthquake in an "open", vertically fractured, medium. This study is designed to investigate the movement of water in a fractured medium in response to stress changes in the rock matrix due to an earthquake which, in turn, produce fluid pressure gradients and accelerated movement of the water. Further, local reduction of the fluid pressure below the ambient level results in degassing of the water, so that a multiphase flow may occur and such effects are included in the modeling. Our objective here is, therefore, to obtain estimates of the magnitude and character of pressure driven water and gas flows resulting from earthquakes under conditions that could prevail at the Yucca Mountain site.

While this modeling is preliminary in the sense that it neglects certain dynamical effects that could be important and is not broad ranging enough to explore the full range of conditions and material parameters that may be appropriate to this site, it nevertheless provides indications of what total volumes and rates of flow might occur. Hence it provides a quantitative test of one aspect of the model proposed by Szymanski, that is a test of whether seismic pumping of significant magnitude may be possible at this site.

Section VIII addresses some of the consequences of the water and gas flooding that could occur as a result of seismic pumping and convection following a large tectonic event. Our purpose is to gauge the consequences of tectonically induced water and gas movement into the planned repository area and thereby gain a better perspective of the magnitude and nature of the hazard involved.

Section IX lists all the consensus statements by the full panel regarding the Szymanski Model. Additional conclusions from this minority report, regarding the Szymanski model and its relevance, are given in Section X. Finally, in Section XI, we give a general integrated discussion of the evidence, conclusions and recommendations of this study, including the full panel consensus views, as they pertain to the suitability of the Yucca Mountain site as a high level nuclear waste repository.

II. Szymanski's Cyclic Hydro-Tectonic (CHT) Model

The Szymanski reports [5] are lengthy and demand careful study. For the convenience of the reader of this report we will outline the essential elements of the CHT model as it is described by Szymanski in these reports and in various conversations we have had with him during this study. We feel that a brief synthesis of the essential features of the model, incorporating his verbal explanations and elaborations as well as the essentials from the reports, may clarify the reader's understanding of his conceptual model. In addition, we feel that it is necessary to establish a logical foundation for the later discussions in this report. Although the form of presentation and the description of processes and mechanisms is our own, we feel that our discussion accurately presents the CHT model that Szymanski has described and used in his interpretations.

The essential and most striking feature of Szymanski's model is the emphasis on nonlinear dynamical coupling between tectonic phenomena, which includes both earthquakes and volcanic activity, and the hydrological state of the upper crust. In broad terms he has focused on the known coupling between fluid transport in a fractured medium and the state of stress and temperature in the medium. More specifically, he has taken note of the fact that, in some circumstances, open fractures can be produced by tectonic stresses within the upper crust and that the fluid storage capacity and hydrological permeability can be dominated by the presence of these fractures. The open fractures, however distributed and whether fluid saturated and interconnected or not, must be in equilibrium with the prevailing stress field in the medium so that a change in the tectonic stress, which can be rapid and large in case of an earthquake or as a consequence of volcanic activity, will close some fractures and open others and, in extreme cases, create new fractures as a material response to these stress changes. This can therefore result in drastic spatial and temporal changes in the storage capacity and permeability of the solid medium and result in rather rapid dynamical changes in the distribution of water within the medium.

One such dynamically coupled flow process is "seismic pumping" resulting from local reductions in storage capacity and associated transient over-pressurization, producing rapid outward water flows. In addition, Szymanski notes that thermal gradients in the crust, especially the upper crust, are large in most tectonic areas and particularly at Yucca Mountain. Citing measured values of these gradients ranging from 20°C / km. to about 50°C / km., he points out that these values are well within the range of thermal instability for water in a highly permeable solid and that one would therefore expect local convection of the water at depth in the saturated zone at the present time. Furthermore, he notes that initiation and changes of convective patterns due to tectonically induced changes in the fracture controlled permeability and storage capacity could occur in zones of high thermal gradients. Consequently, he expects significant changes in convective patterns of flow due to a large earthquake, which would be expected to alter dramatically the stress field and the spatial configuration of open fractures. Thus, he points out that an earthquake may lead, in some cases, to initiation of major long term up-welling of water from depth into previously unsaturated zones as the result of changes in permeability and porosity. Likewise, he notes that renewed volcanism could be expected to increase thermal gradients and also increase fracture permeability in some localized areas; thereby also producing the onset of strong convective up-welling in these zones due to the changed hydrological and thermodynamic conditions in the system.

Consequently, Szymanski expects initiation of both rapid transient flows and slower, but longer enduring, convective flows in a highly fractured permeable medium in response to tec-

YUCCA MOUNTAIN HYDROTECTONIC SYSTEM

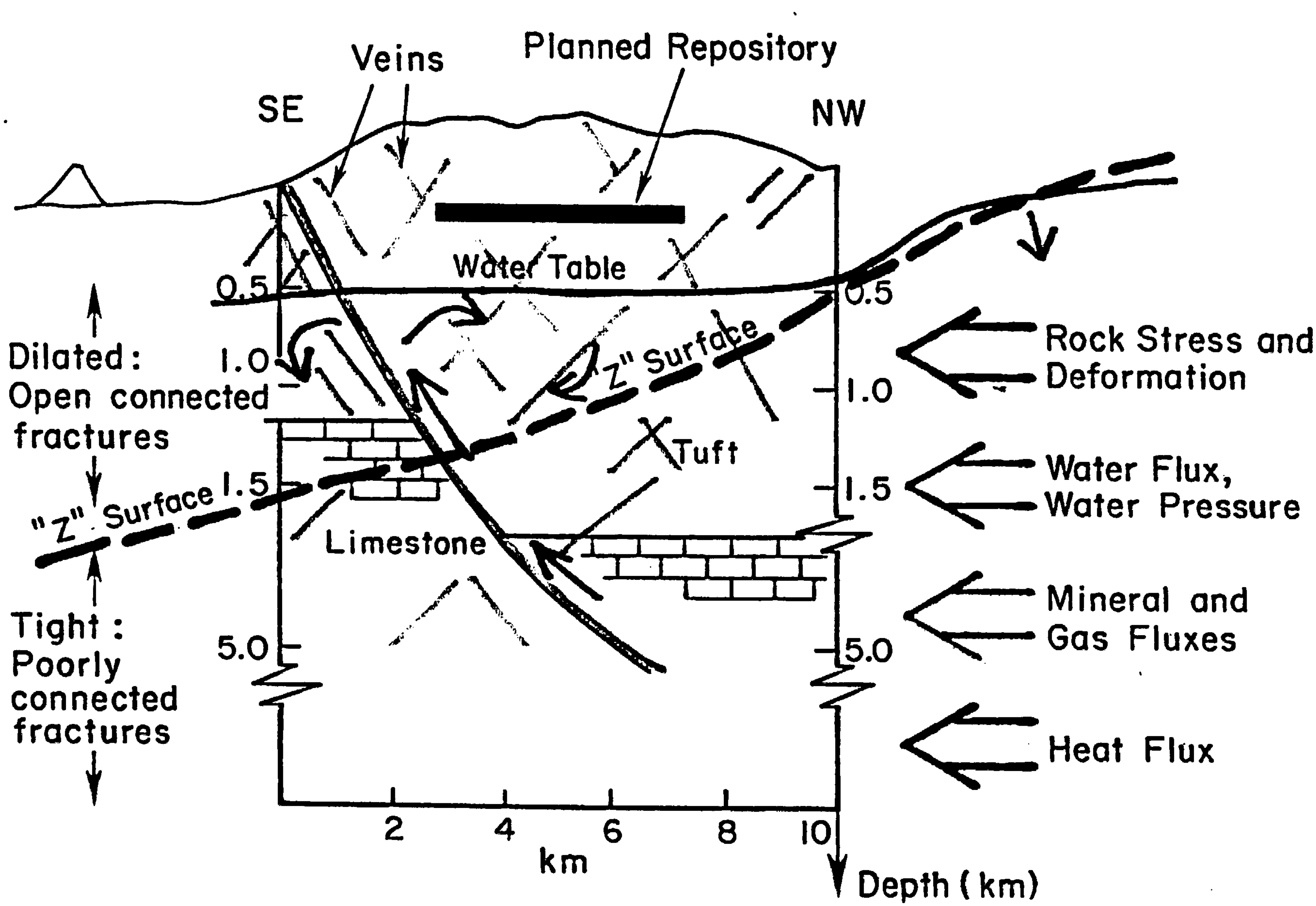


Fig. 1. - Schematic of the current state of Yucca Mountain system as represented in Szymanski's hydrotectonic model. The "system" is defined to be the physical region encompassing the proposed repository and the region within a kilometer or two surrounding it and extending in depth to about 10 km into the upper crust. The "Z surfacc" shown is conceived to separate a dilated zone above from a non-dilatant zone below. The arrows indicate paths for convection of the water along faults transecting the Yucca Mountain system. The arrows on the right represent the types of fluxes and forces at all the boundaries of the system. The rise of the water table to the Northwest of the proposed repository is indicated on the right of the diagram, along with the (expected) rise in the "Z surface".

tonic activity in the form of either a large earthquake or volcanism. In association with such flows he expects deposition of minerals as the fluids move from depth to a lower pressure and cooler environment, so that fracture filling will occur as these flow processes continue. He therefore expects to observe a period of fracture controlled vein deposition of minerals carried by the water from depth and a slow constriction and decrease in the convective cell size and flow rate as the fractures are partially or totally filled by precipitating minerals.

In applying these general concepts to a description of the tectonic and hydrological environment at Yucca Mountain, Szymanski has advanced a specific, albeit qualitative, model that he feels is required on the basis of the applicable physics and the observed geologic, tectonic and hydrologic setting specific to this site. The character of the model, which might be termed a cyclic hydro-tectonic model, is described in terms of a progression of physical states through which the system (taken to be the medium underlying the mountain and its immediate surroundings to a depth of about 10 km) progresses or evolves. A definition of the spatial extent and character of the Yucca Mountain "system" is illustrated in Figure 1.

The evolution of the state of the system is expected to have a cyclic character in that it repeats itself in response to slow tectonic stress increases followed by recurrent rapid decreases during an earthquake or volcanic event, where such singular events mark the end of one cycle and the beginning of the next. Beginning at the current state of the Yucca Mountain system, this cyclic model is illustrated in Figure 2 and may be described as follows:

The Contemporary, Meta-Stable State.

The system is characterized by a high density of open, mostly vertical, fractures to considerable depth, well below the current water table level at nearly 500 meters below the surface, so that the medium is in a dilatant state due to tectonic stresses. The open fractures are a manifesta-

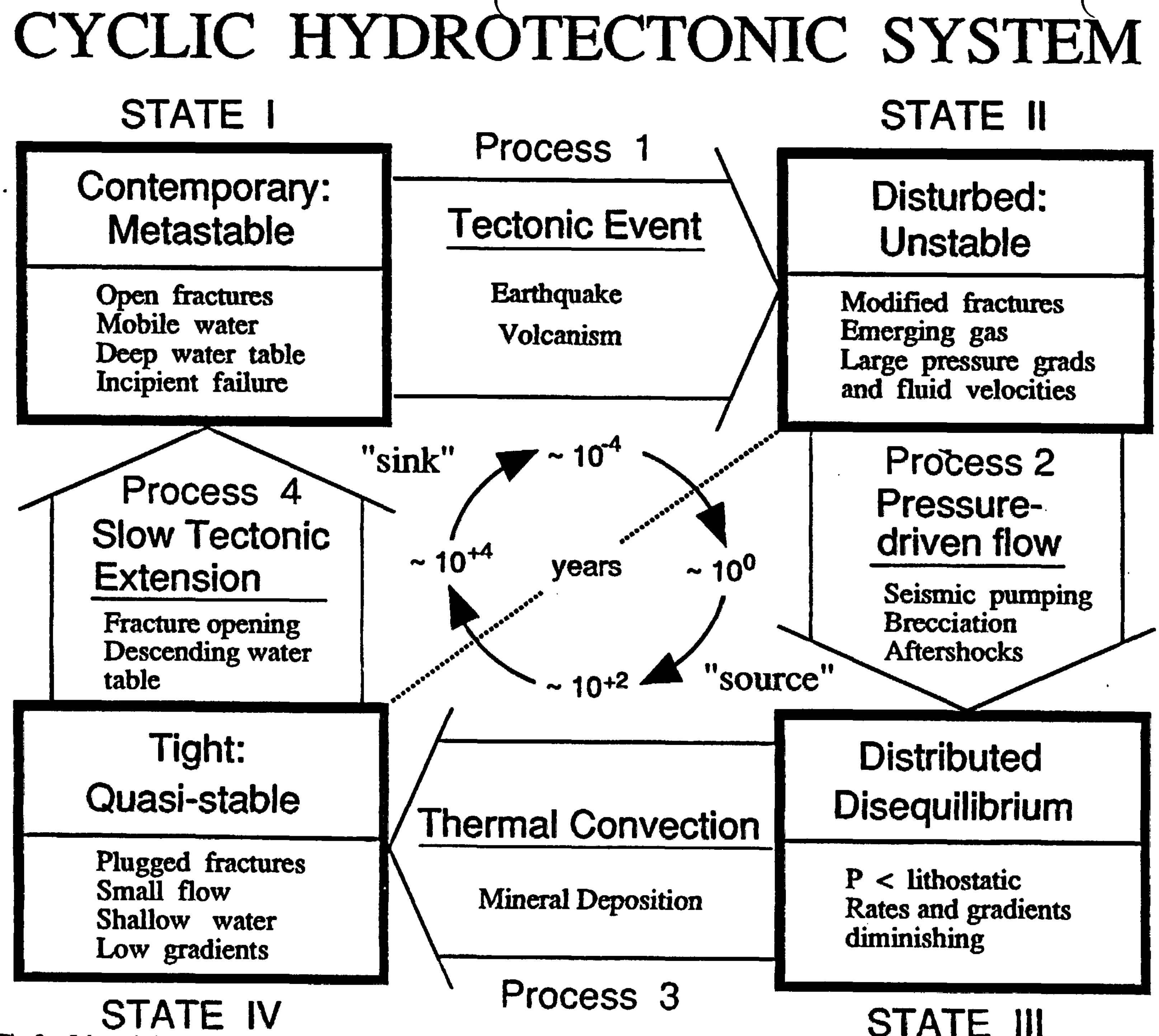


Fig. 2. - Schematic indicating states of the system and the processes expected, by Szymanski, to produce a cyclical evolution from one state to another over time. The roughly estimated interval times for these processes are indicated in the center of the diagram.

tion of the predominantly extensional tectonic strains and are in equilibrium with the local stress field (which is a superposition of lithostatic and tectonic fields). Because of the existence of many open fractures, the local stresses in the medium around such fractures must deviate appreciably from the average stress level in the system in order to maintain static equilibrium.

The very low level of the water table is a consequence of the fracture controlled high storage capacity within the medium, resulting from the high density of open fractures, and also because of the high permeability of the medium, which is a consequence of the relatively large numbers of connected open fractures that provide low impedance pathways for vertical flow to great depth. Thus the system can be classified as a "hydrological sink"; in that current water flow is largely from the surface downward to the water table at considerable depth. Because of the open fracture system above the water table, the water in open connected fractures for a considerable depth below the water table is at hydrostatic pressure relative to the top of the water table, rather than at lithostatic pressures.

The thermal gradients within the system are inferred to be high, varying from 20°C/km near the surface to 40 to 60°C/km at depths below 1 to 2 km. This implies localized connective water flows in the connected fractures which reduce the shallow thermal gradients below the water table while the presence of larger thermal gradients at depth imply lower permeability and little or no wide-spread convection of the water through connected fractures. The depth level above which many fractures are abundantly open and interconnected is termed the "Z level" by Szymanski. It would therefore be the depth level at which the fluid pressure in the fractured zone below the water table began to rapidly increase from hydrostatic and also where the temperature gradient with depth should begin to rapidly increase, from one in a freely convective zone (near 20°C/km) to a higher level in the 40 to 50°C/km range. This occurs because the thermal gradients are controlled by the possibility of water flow through interconnected open fractures; that is the convective flow in the open fracture zone below the water table reduces the thermal gradients.

Just a few kilometers to the north of the Yucca Mountain system, the water table is observed to be higher, by several hundred meters, than at Yucca Mountain and this is interpreted by Szymanski to be, most probably, a consequence of a reduction in the numbers (density) of open vertically connected fractures in this area. This reduction may be due, primarily, to a change in orientation and magnitude of the tectonic stresses from incipient failure in shear to more isotropic at lithostatic pressures.

This description of the current state of the Yucca Mountain system, and its immediate surroundings, is summarized schematically in Figure (1.).

Disturbed State following a Tectonic Event.

In the CHT model, the current Yucca Mountain system is judged to be meta-stable in that it can accommodate slow, small changes in the external stress conditions and the hydrodynamic and thermal fluxes and remain, for a limited time, in a state in which no major hydrologic changes occur. However, any rapid change of moderate to large magnitude in the external stress conditions or fluxes into the system would almost certainly cause the mechanical and hydrodynamic state of the system to change dramatically. This is considered to be not only likely but unavoidable because of the necessity of corresponding rapid changes in fracture apertures in response to stress changes on the one hand and the strong coupling between fracture controlled fluid pressures, storage capacity and flow permeability, which directly affect pressure driven and thermally driven water flows through the fractures, on the other hand. Of the changes most affecting the system stability, direct tectonic stress changes would therefore be the most important. However, thermal flux changes would also be critical since a change in heat flow from beneath the system resulting from volcanism would increase thermal gradients which could produce convective instability of the water in a previously stable fluid-filled fracture system.

In addition, Szymanski argues that external changes of stress conditions on the system boundaries and changes of fluxes through the boundaries into the system give rise to slow changes in the internal tectonic stress levels within the system and that these must lead to instability, in that eventually a large earthquake can be expected to occur resulting in major stress changes throughout the system. Such an event would be expected to be initiated near the lower boundary of the system, below about 5 km, with a failure zone rapidly extending up to the surface. The earthquake would reset the system stresses so that some existing open fractures would rapidly close down while some could be created and opened. In view of the tensional tectonic stresses prevailing, it is most probable that such an earthquake would produce a narrow failure zone nearly perpendicular to the free surface at the shallower depths with a slowly decreasing dip angle with increasing depth, becoming nearly parallel to the free surface at perhaps greater depths, in the range from 5 to 10 km. That is, the expected event would produce a so-called "listric fault". The geometry of such a failure zone, or fault, is illustrated in Figure 3.

Szymanski maintains that, based on current rather rough estimates of faulting patterns in the general area of Yucca Mountain, earthquakes with magnitudes in the range from 6 to 7 could be expected to occur every few thousand years. Given the current high differential stress levels in the mountain [6], [7], [8] and presumably in the upper crust beneath it, he considers the time to the next seismic event to be relatively short, perhaps less than one hundred years.

An earthquake in the magnitude range indicated, occurring within the Yucca Mountain crustal zone, is expected to produce wide-spread, relatively sudden, relaxation of the tectonic

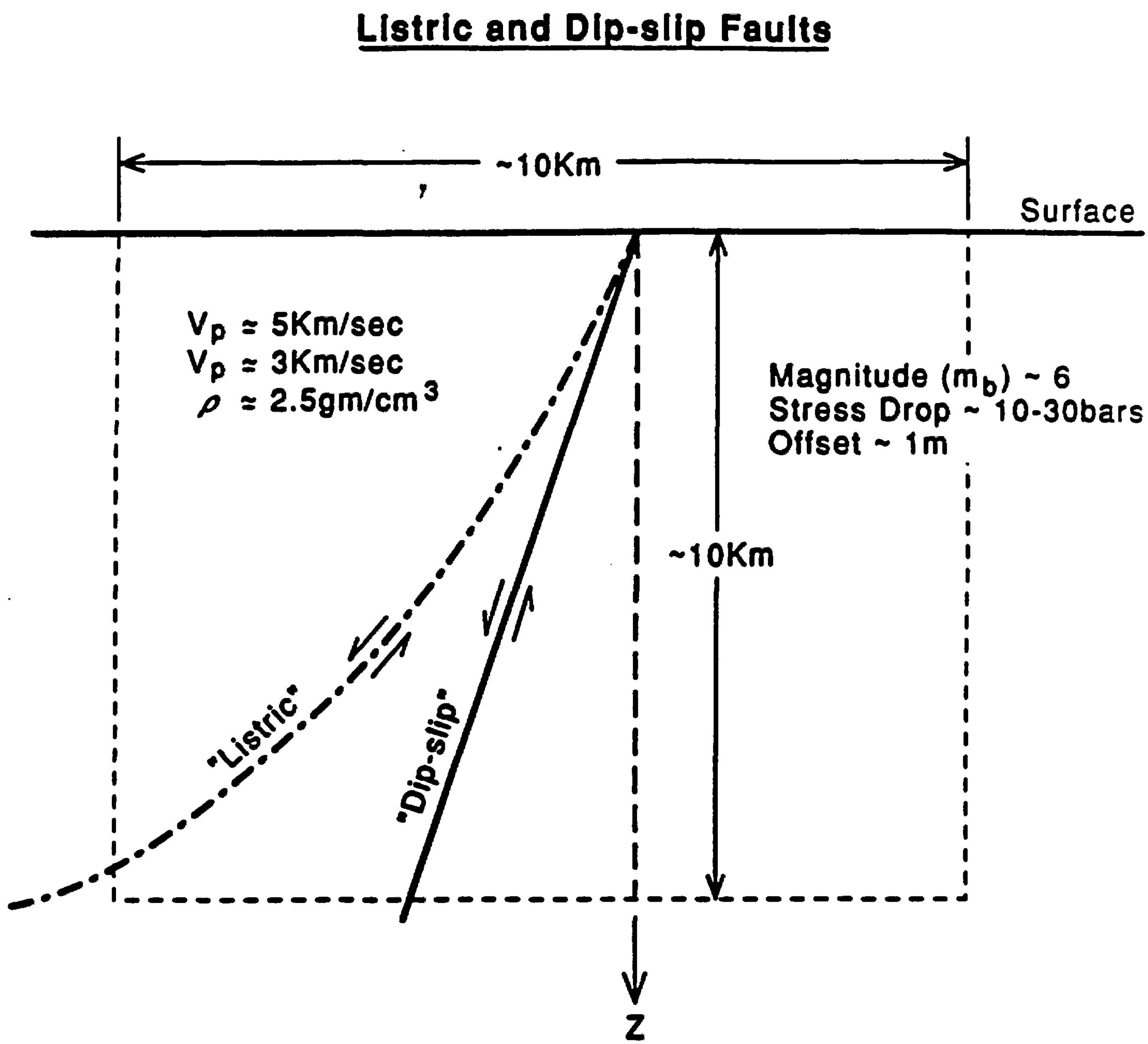


Fig. 3. - Listric and Dip-Slip faults with source parameters typical of a (m_b) magnitude 6 earthquake.

stresses; so that many fractures would try to close and, below the water table particularly, the fluid pressure in previously connected fractures would rapidly rise from hydrostatic to levels near lithostatic. This pressure rise would result in a pressure driven flow of the water, generally upward due to the prevailing fracture orientation, away from the most highly pressured zones. Further, the fluid pressures in the unconnected water saturated fractures and pores would also initially increase to a value far above the current minimum principal stress level. That is, to a magnitude in excess of the new minimum principal stress level in the rock which, near the failure zone at least, would be near lithostatic. Such an increase in fluid pressure in unconnected fractures could produce fracture growth by extension and interconnection of these previously isolated fractures to other neighboring fractures and a net increase in permeability and pressurized flow through the network of fractures. Thus, at least some of the previously immobile pore and fracture water is expected to be able to move through the system.

Adjacent to the fault zone, that is essentially within the fracture zone produced by a normal dip-slip type earthquake, it is expected that the density of open fractures would be very high from the surface to considerable depth and so provide a connected open fracture pathway for any upward fluid flow from depth towards the surface. Therefore, in addition to a general volume distributed flow due to wide spread rapid pressurization of the fracture and pore water, it is expected that enhanced and rapid flow would occur along, or within, the relatively narrow, steeply dipping, upper section of the fault zone due to its high permeability and connection to pressurized water at depth.

As the seismic pumping phenomena described is expected to be transient and of relatively short time duration. It nevertheless is expected to result in an appreciable total flow volume, on the order from 10^8 m^3 to 10^9 m^3 for a large earthquake. A significant fraction of the flow volume is expected to be extruded at the surface, along the fault trace itself. The duration of the flow would be controlled by the permeability of the medium and the spatial extent and magnitude of the pressurization, with water transport reducing the steep pressure gradients and sharp flow transients after a time period that is expected to be from months to a few years. During this period of flow it is expected that some quite modest degree of chemical deposition would occur, principally from waters originating from considerable depth (2 to 10 km.) moving upward into near surface zones of lower pressure and temperature.

The expected behavior of the system is therefore a slow transition from a meta-stable dilatant, high tectonic stress state to an unstable state resulting in mechanical failure and an earthquake. The consequence of the earthquake and the associated material failure and tectonic stress field changes would be a major change of storage capacity in the rock and a relatively short transient period of seismic pumping of water from depth into the under-saturated zone above the water table and to the surface, particularly along the narrow fault zone formed by the event. The upward water movement should also result in the deposition of small quantities of carbonates and/or opal in the under-saturated zone and at the surface. Thus, the transient movement of water, coupled with the decrease in storage capacity, would result in an upward migration of the "Z surface", that is the surface above which the fracture system is largely interconnected and open and a similar upward migration of the water table surface to a shallower depth, reflecting the overall decrease in storage capacity. The local, upward movement of these surfaces could be from tens of meters to hundreds of meters, depending on the type, magnitude and precise location of the earthquake. The effect of such an earthquake is, therefore, to reset, or change, the entire hydrological and tectonic state of the system.

Distributed Disequilibrium and Thermal Convection.

Following the rapid changes in stress, medium porosity and permeability, and the transient pressure driven "seismic pumping", it is expected that a relatively long period of convective, thermally driven, water flow would occur. This is expected to occur because of localized increases in the density of connected fractures in and near the earthquake fault zone, resulting in increased permeability in the region of high thermal gradients below the "Z surface". With such a change, the water is able to more readily flow through the new fracture system at depth and, because of the high thermal gradients, will begin to convect vigorously. This convective process is expected to occur in localized cells which are long lasting and initially quite energetic in view of the high temperature gradients below about 2 km. It is therefore expected to be able to carry water from great depths to the surface. During this convective period large volumes of water are expected to move from the vicinity of, and even from below, the earthquake hypocenter along zones where the density of connected fractures has been greatly increased by the earthquake. Such regions occur within the narrow failure zone itself and in zones where the tension in the rock matrix increases because of the large scale failure. (The pattern of pressure changes in the medium surrounding the fault zone is roughly quadrupolar, with alternating lobes of compression and dilatation, so that at least some zones within the system will experience increased dilation of existing fractures and additional fracturing.)

As the high temperature water moves upward it is expected that the water would be saturated with CO_2, calcium and silica from the limestone and tuff formations at depth. As it cooled, decompressed and degassed during upward transport, it would deposit opal or calcium carbonate in the fractures and along the surface downslope from surface intersections of deeply penetrating fault and fracture zones. An important characteristic of this flow, and the associated mineral deposition, is that it involves water transport from great depth, from 5 to 10 km. or more. Therefore the flow would consist, in part, of water carrying isotopes of oxygen, carbon, uranium, etc., that are characteristic of "old", deep seated meteoric water that has resided in Paleozoic limestones and the underlying Precambrian basement for many thousands of years. As this latter water is convected upward it would mix with shallower water residing in the younger tuffs, so that the isotopic signature of the water depositing the minerals would be a composite of the isotopic characteristics of both shallow and deep seated water beneath the mountain.

Within one episode of this convective process, the deposition of minerals would slowly plug the fracture system, and decrease the density of connected fractures, so that the process would slow and eventually stop. This is estimated to take of the order of many hundreds of years. At the end of this convective stage it is expected that the storage capacity and permeability would be relatively low and that the water table would have been elevated to a much shallower depth, perhaps several hundred meters higher than its present level. Likewise the "Z" level would also be shallow, probably quite near the surface.

The Quasi-Stable State with Gradual Tectonic Extension and Shear.

At the end of the convective episode the system would be in a low internal energy state; with low tectonic stresses and with temperature and pressure gradients at low levels. Because the hydrological storage capacity and permeability would also be low, there would be no potential for large volume rapid water flows. The system, at this stage, could be considered to be essentially stable, with the only change being its response to the slow continuing build-up of tectonic stress. Such a slow stress increase, which is predominately extensional, would eventually begin to produce tension fractures and reopening of fractures previously closed by the last large earthquake, or volcanic episode. The system would therefore be expected to "migrate" towards the meta-stable state observed at the present time. That is, as fractures opened and interconnected the hydrological storage capacity and permeability would increase and the water table would drop. The "Z" level would also, of course, be expected to migrate to a greater depth as more fractures were opened at progressively deeper levels in response to the ever increasing tectonic extension. At a later stage, when the average tectonic stress levels in the system had built back up to high levels, the water table and "Z" level would both be at relatively great depth, as at present, and the system would be in a state which could shortly become unstable with continued increases in tectonic stresses. Thus, after a long period (thousands of years) of slow increase in tectonic stress the entire cycle would repeat itself. Because of the abundance of calcium carbonate veins and fracture fillings, as well as surface deposits, with ages spanning many hundreds of thousands of years, it is thought that the cycle has been repeated many times; perhaps hundreds of times.

This cyclic model, as described by Szymanski and as summarized above, describes the sequence of events that is expected to occur in response to a large earthquake within or close to the Yucca Mountain system. A similar sequence is expected to occur as a consequence of the sudden onset of volcanism involving either extrusion or intrusion of magmatic material. In this case rapid changes in the stress field are expected, along with earthquakes, as well as major changes in flux levels at the boundaries of the system. When such an event actually involves intrusion of material into or just beneath the system, flows of gas and fluid would be expected and could lead to particularly energetic phenomena, including extrusion of high temperature water along with highly energetic gas flows producing intense fracturing and brecciation. It would also be expected to produce intense hydrothermal alteration and vein mineralization in the fractured and faulted medium. Thus, the expected sequence of flow phenomena would be similar to that described for a large earthquake, but more energetically extreme.

III. Alternate Hydro-Geologic Models for the Yucca Mountain System: The "Pedogenic Model"

To place the comparison of observations with conceptual models in a wider and more definitive context, we also consider an alternative to Szymanski's model in order to check whether another reasonable explanation of the observations is available. In this regard, the critical question is whether up-welling water is the source of the extensive opal-carbonate deposits observed or whether these deposits, or at least those near the surface, can be explained by evaporation and transportation (by plant roots) involving only descending meteoric water. If a strong case can be made in favor of rain water origins for the deposits observed, then the necessity of an explanation of their existence involving up-welling water deposition is diminished and the likelihood that the hydro-tectonic processes described could produce strong hydrological flows bringing water and gas to the surface is greatly reduced. In this case the likelihood of occurrence of the most serious hazard, namely rapid large-volume intrusion of water and gas into the repository region, would also be greatly reduced.

A complete definition and discussion of the alternative to Szymanski's model for the Yucca Mountain system has not, to the knowledge of the authors, been published in the professional literature or in a government report. Rather, the model has emerged in "bits and pieces" in publications focused on narrower issues, such as local hydrology or the isotopic characteristics of Yucca Mountain opal-carbonate veins [9]. Based on this information however, a rough "model" can be defined at this stage and is useful for comparative purposes. In the following we outline the relevant essentials of this model which, because of its most important feature, will be referred to as the Pedogenic Model".

Hydrologic and Tectonic Features of the "Pedogenic Model"

The Yucca Mountain system, as defined earlier, is considered to be presently in a quasi-stable tectonic state, with moderate tectonic stresses prevailing. The hydrological state is characterized by a very deep water table (about 500 meters beneath the mountain) and fracture controlled permeability at depths above the water table and probably somewhat below it, but connected fractures are not pervasive to great depths in the upper crust. The hydrological state is reasonably stable, in that the occurrence of a major tectonic event, in particular an earthquake, could perturb the hydrological equilibrium, but not in a very drastic manner that would involve either short term very large scale water flow or large long term changes in the water table. Only in the event of volcanic activity directly beneath the mountain, at shallow depths, might there be any major disturbance in the water table due to greater heat flux or actual magma and gas intrusion.

Thus, the possible occurrence of an earthquake along one of the existing major faults on the margins of the mountain is expected to produce, perhaps, some seismic pumping of relatively small amounts of water locally near the fault zone. In terms of hazards to a repository, the earthquake could produce strong shaking at repository levels and, if the faulting actually intersected the repository, some fairly large offsets (of the order of a meter) along fault surfaces within the repository. However, only the unlikely intersection of the repository by a new fault would pose any danger of loss of containment.

Because of the weakness of the coupling of tectonic effects to hydrological conditions and flows, rapid water up-welling and longer term changes in the water table would be of relatively low magnitude and confined spatially and, overall, a second order perturbation relative to lithologically controlled gravity forced flow. The hazard posed by tectonically coupled pressure-forced flows (seismic pumping) is therefore considered small.

Similarly, widespread changes in the deep fracture porosity and permeability due to an earthquake are expected to be relatively small and localized in the vicinity of earthquake faulting in any case, so that without a major change in heat flux into the system, no widespread thermal convection in the water would be likely following a major earthquake. Again, any thermally driven convection of water would be expected to be weak and localized near the failure zone at depth and not able to reach the repository level. Only a volcanic episode, essentially within or very near the boundaries of the system, might produce heat flux changes sufficient to result in thermal instability and convection in the water. This is considered to be an unlikely event at Yucca Mountain. Thus the system is viewed as, essentially, hydrologically stable.

Deposition of Vein and Surface Calcite-Opal Minerals in the Pedogenic Model

The incidence of calcite-opal surface deposits are interpreted to be largely due to near surface evaporation of meteoric waters that have taken up calcium, carbon dioxide and silica into solution [9,38]. In addition, particularly in the case of vein-like deposits, plant roots are considered as sources of calcite deposits by processes of transportation. Thus, rain water is expected to dissolve wind blown calcium carbonate deposited along the surface, as well as silica from the surface exposed tuffs, and redeposit these minerals upon evaporation in particularly suitable locals where the topography focuses drainage and allows the evaporative processes to accumulate the minerals in surface parallel deposits. Because the plants also absorb water, they will produce mineral deposits with characteristic features that include the carbon isotope signatures from the particular plants involved.

Because fracture zones, especially highly fractured major fault zones, can form traps for surface water run-off, it is expected that inflows into such zones can be relatively large when the local topography provides an extended source area for rain water drainage to the fracture zone.

Thus, under appropriate surface conditions it is expected that the water would drain downward into the fractures and upon evaporation deposit calcites and opals in layers along the fracture walls. With recurrent faulting, fractures that were filled or partially filled could be reopened and experience another epoch of deposition by this process. Additionally, plants growing within the relatively water rich fracture zones could produce some mineral deposits at depth due to the extension of root systems several tens of meters below the surface in some cases.

Since these depositional processes involve surface drainage of rain water and near surface evaporation for the most part, the deposits so formed are termed "pedogenic", that is, literally, "soil-forming". Thus, deposition is expected to be at shallow depths by evaporation or by root transportation at low temperatures and pressures. Further, the process will occur at a relatively low rate which is chiefly dependent on the availability of wind transported calcite, the amount of rainfall and the local topography which governs the water volumes available for deposition and where such deposition can occur.

In addition to original deposition of minerals, the pedogenic mechanisms may rework older deposits that could be of similar origin or of other origins, such as calcite-opal veins of hydrothermal origin. In instances where calcium and silica are dissolved and redeposited, the original deposits can be expected to take on isotopic and morphological characteristics that are determined by the chemistry of the rain water involved and the physical environment (*eg*. slope conditions) in the zone of re-deposition. This re-working can therefore have the effect of altering age determinations for a deposit as well as altering its physical and chemical characteristics.

General Features and Rates of Deposition

Whatever other mechanisms and processes may be active and responsible for calcite and other mineral deposits at Yucca Mountain and similar sites in desert environments, there is little doubt that the pedogenic mechanisms described do operate, slowly re-working old deposits near the surface and also depositing new ones in some select areas. Thus, from this point of view, it is quite certain that these mechanisms play a part in the geology and geochemistry of the vein calcites and surface calcretes at the Yucca Mountain site.

An important question, however, is whether such a low depositional rate process can account for the large volumes of calcites observed both near the surface and in veins at depth in the mountain. Since there is little rain water accessibility to calcite, except that which is laid down by the wind carrying particles from limestone formations in mountains several miles away, one can estimate maximal rates of deposition by measuring the rates at which such dust is accumulated. Data from dust traps at Yucca Mountain [41] indicate that, on average, of the order of 1 cm. of calcite per 10,000 years can be deposited by this process, if all the dust blown calcite is "captured" and deposited. Accounting for the likelihood of an extended source area for dissolution and runoff to a restricted area for deposition, the maximum rate could perhaps be a factor of 10 greater depending on the local terrain; so that a rate of 10 cm. per 10,000 years could conceivably occur at some locales. In this regard, the the maximum depositional rate for pedogenic carbonate in the Southwestern U.S. is reported to be about 0.5 gm/cm^2 per thousand years [10], which translates into about 2 cm of carbonate per 10,000 years. These rates are much lower than that to be expected from calcium rich up-welling water from the limestones beneath Yucca Mountain, for which rates of the order of 1 cm. per year or greater can be expected. Thus the rates of deposition by the two mechanisms appear to be different by a factor of at least 1000. This rate difference will clearly be important in assessing the origins of the calcite-opal veins and calcites at Yucca Mountain and ultimately in assessing the observational basis for the flow model proposed by Szymanski.

Other differences in model predictions, besides modes and forms of mineral deposition, are also of importance in the assessment of these models; specifically the shallow depositional characteristics of pedogenic processes as compared to the likelihood of deposition throughout an extensive depth section by the up-welling flows that are associated with the hydro-tectonic model. In the following sections these and other differences between the model predictions will be useful, if not definitive, in the evaluation of the physical and geochemical field evidence.

IV. Evaluation of the Principal Geologic Field Observations: Faulting, Volcanism and Calcite-Opal Veins and Calcretes

A major problem in assessing the importance of the Szymanski report relates to the magnitude of the effects inherent in his model. It was recognized by the panel that the veins which crop out in and around Yucca Mountain, and their behavior at depth, constitute critical evidence as regards the potential magnitude to which the ground-water level may be raised above its present position. We therefore discuss the data related to these veins and surface deposits in some detail.

In this section we shall outline the evidence which has led us to the conclusion that the veins which crop out at the surface throughout the Yucca Mountain area are the result of upwelling fluids coming from considerable depth. We also conclude that in many instances this vein-fluid poured out through fissures which intersect the topographic surface and that this process has been repeated in the area many times and has resulted in the development of extensive vein systems, which contain calcite and opal, and has also given rise to the generation of thick and sometimes extensive sheets of tufa or calcrete on the topographical surface.

We take the extensive emplacement of veins at the surface and at depth in the area as evidence that the water-table, or transient excursions of the water-table, have from time to time reached the surface. Thus, these phases of upward movement of the water-table have attained altitudes higher than that at which the proposed repository is supposed to be emplaced. We argue, in a later section, that such migrations of the water-table could place at risk the integrity of the proposed repository.

In view of the fact that other interpretations of the vein and slope parallel calcite deposits have been made using the Pedogenic Model described in Section III, we contrast these interpretations with our own. The alternative interpretations are that either the deposits are entirely due to descending rain water deposition of calcite and opaline silica along the surface and in accessible fractures and faults, over a relatively long period of time, or that meteoric water has dissolved and redeposited ("reworked") old calcite and silica deposits originating from hydrothermal deposition during the last very active epoch of volcanism, which ended some 10 million years ago. These processes are characterized by very low depositional (or redepositional) rates and both are, by their very nature, confined to the near surface zone which might extend, at most, to a depth of a few tens of meters.

General Characteristics of Veins and Vein Minerals

The conventional interpretation of the development of veins in sediments and metasediments is that the infilling material (commonly, calcite and silica) has been deposited on the walls of fractures by the precipitation of these minerals from saturated solutions as the fluids pass through the fractures in the sediments. (Thin quartz bodies which resemble veins may also result from the pressure-solution-exsolution process, but these need not concern us here.)

The vast majority of geologists consider that the source of fluids from which precipitation occurs is the result of the expulsion of interstitial water and brine, contained in sediments and some volcanic rocks, following compaction and/or orogenic processes. An additional source of fluid is attributed to the dehydration reactions that can occur during the pro-grade metamorphism of sediments. These fluids may flow from below to the surface (whether this be sub-aerial or sub-marine) as a "single pass" operation.

Alternatively, when thermal and tectonic conditions are suitable, convection of the interstitial water occurs. This results in a "multi-pass" process that can give rise to a relatively high proportion of vein to country-rock. Another manifestation of this multi-pass process is that it may concentrate relatively insoluble minerals, such as gold, within the veins. (Gold-bearing veins are known to occur in the vicinity of Yucca Mountain[17].)

The solubility characteristics of silica and calcite are obviously important in vein formation [34]. The solubility of silica at temperatures below 300°C is mainly unaffected by pressure and is influenced only by temperature and the pH value of the water in which it is dissolved. At 300°C as much as 0.1 percent of SiO_2 can be held in solution (at pH values from 2-8). The solubility decreases with temperature in a linear fashion so that at a temperature of 150°C, and below, the solubility is reduced to a few parts per million. However, at 20°C the solubility of amorphous silica is very much higher, at about 100 p.p.m.. Also, at pH values of greater than 9 there is a rapid increase in the solubility of SiO_2. However, we mention in passing that the pH value of rain-water is usually about 3.0. It requires very special and unusual conditions to bring about very high pH values in ground-water, especially near the top of a mountain. It is, for example, unlikely, in the extreme, that extensive pools containing highly alkaline solutions (with high values of pH) ever existed near the crest of Yucca Mountain.

The solubility of calcite is also controlled in part by temperature. However, this mineral is unusual in that it exhibits a decrease in solubility with increase of temperature of solution. The temperature effect is, however, over-ridden by the partial pressure of CO_2 in solution; typically without CO_2, calcite is relatively insoluble in water. The maximum partial pressure that can be sustained in solution is related to the total fluid pressure (p). In up-welling water, the degassing of the fluid can result in precipitation of calcite. Water extruded at the surface, or that accumulates from rain, will contain no more than that proportion of CO_2 that can remain in solution at one atmosphere of pressure. In order that calcite can be induced to precipitate from such surface water, it is necessary to reduce the volume of water by evaporation. We will return to this point

a

b

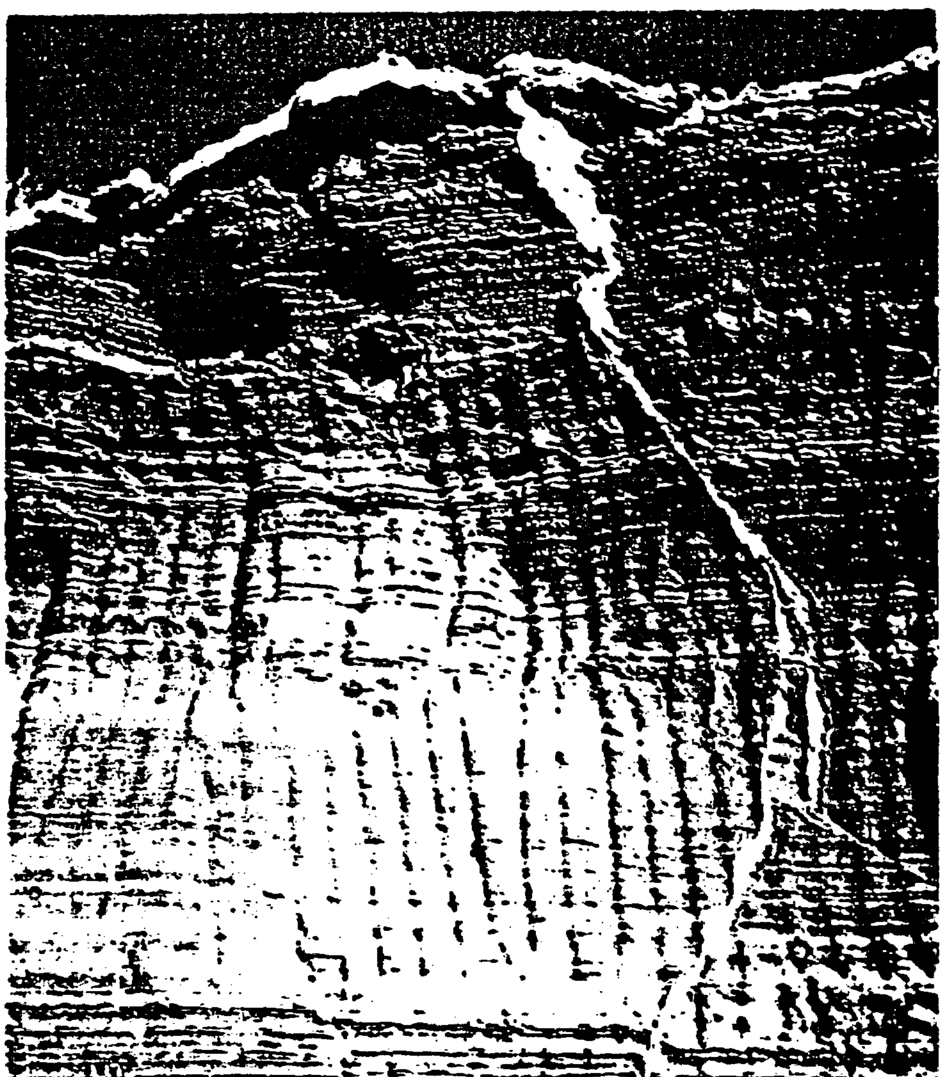


Fig. 4. - Views of a carbonate vein exposed in a quarry face located approximately 20 km. south of McCarron Airport, Las Vegas, N.V.

a] A general view from which the scale of the structure can be inferred.

b] A carbonate vein that cuts through poorly cemented, bedded ash and gives way to a carbonate apron, or pediment, at the topographical surface. Although the view is oblique, it can be inferred that the apron is thickest immediately adjacent to the intersection of the vein with the topographic surface

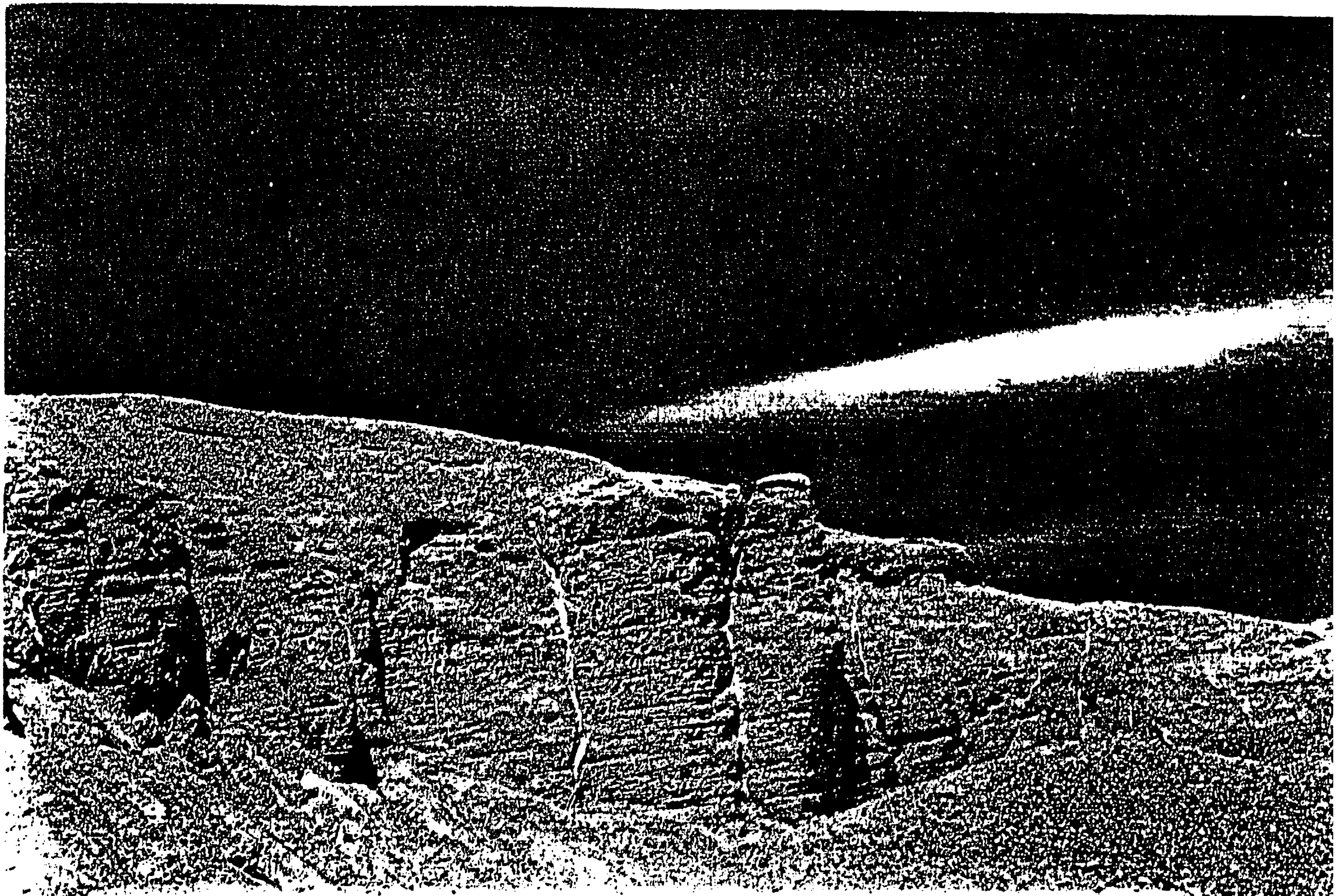


Fig. 5. - A view of veins exposed in the cliff face that borders, to the east, the highway as it descends into the southern part of Death Valley. The main veins are at least a metre thick and extend vertically for at least 150 m. As in Fig. 1., the veins give way to a carbonate [tufa] apron at the topographic surface. The crystals in the veins at the base of the cliff attain lengths of several centimeters, while the apron tufa is extremely fine grain.

when discussing the size of crystals that are likely to develop in a calcite vein.

In exceptional circumstances, exposure permits one to see clearly the relationship between a vein and the associated pediment of calcrete. This relationship is illustrated in Fig. 4. a and b. This thin calcite vein cuts through, poorly cemented, bedded-ash which crops out about 20 km south of McCarran Airport at Las Vegas, NV. The inset figure (4a) is intended only to show the scale of this relatively small structure. The details of the vein can more clearly be seen in Fig. 4b. Note that the thickness of the pediment appears to be greatest immediately adjacent to the intersection of the vein and the topographic surface. This is a relationship commonly seen where springs deposit minerals at the surface.

When exposure permits, one can usually trace individual veins through considerable vertical distances, as in Fig. 5. This figure shows a series of veins that crop-out in a cliff face bordering Death Valley. The veins are well over one meter thick in places and, it can be inferred, have a vertical extent in excess of 200 m. It is important to note that even though the veins are a consequence of up-welling water in a hydrothermal area, there is no obvious hydrothermal alteration of the country rock adjacent to the veins. Thus the up-welling water was not at very high temperatures at these near surface depths. We can expect, therefore, that some exposed veins in hydrothermal areas will not show associated high temperature alteration of the country rock near the veins while some will, depending on local conditions and the details of the flow process and water chemistry.

Thus, from Figs. 4 and 5, we infer that when the summit of an upward moving plume of a convection-cell intercepts the surface, some of the fluids are lost to the cell and, in sub-aerial conditions, result in the veins cropping out at the surface. In arid or semi-arid conditions these out-flowing fluids can readily give rise to calcretes and related features when calcium-rich limestone are present. Of course, not all calcrete pavements form by this mechanism, but it is clear that in hydrothermal areas the process is common.

One of the features of the veins shown in Fig. 5 is that in the veins exposed at the bottom of the cliff, where they are readily accessible, it can be seen that individual calcite crystals are of the order of several centimeters ih length. In contrast, the veins in Trench 14 exhibit grain sizes of the order of a few microns. There is a tacit assumption, and implied conclusion drawn by some investigators, that the difference in grain size in the two situations is indicative of different modes of emplacement. Hence, the implication is that the near surface deposits are the result directly, or indirectly, of rainwater deposition. However, the grain size in the calcitic tufa at the top of the vein shown in Fig. 5. is also exceedingly small. Therefore, we consider the emplacement of veins in somewhat more detail.

The development of large crystals in such calcite veins permits one to draw two inferences:

1) Large crystals mainly develop in a water-filled hole or fissure (c.f. the crystal forms so commonly seen in geodes).

2) When large crystals develop, one can infer that conditions for intense crystal nucleation do not exist, *i.e.* the solution giving rise to the development of the large crystals is only a little over-saturated.

It will be recalled that calcite is deposited when the partial pressure of CO_2 is reduced. The maximum partial pressure that can be sustained is related to the total fluid pressure (p) of the vein fluid; that is, in a system open to the surface, the maximum amount of CO_2 in solution will be related to the near hydrostatic fluid pressure of the vein-fluid at specific depths. As the vein-fluid approaches the surface, the fluid pressure automatically decreases in magnitude and CO_2 bubbles are generated. The generation of bubbles results in a significant reduction in the

Fig. 6. - Details of a vein, exposed in the vicinity of Yucca Mountain, with an open suture. From the knife, used for scale, it can be inferred that the suture has parted by as much as 0.5 cm. In the field it can be clearly seen that the vein material on either side of the suture exhibits two faint bands, indicating that the vein has developed in two stages. [Unfortunately the quality of photographic reproduction is such that these bands cannot be clearly seen in this figure.]

(average) density of the vein-fluid. This reduction in density, at a specific depth, results in a reduction of the fluid pressure. This further reduction in fluid pressure, in turn, results in the generation of yet more CO_2 bubbles. Near the surface this effect may become so pronounced that the fluid could resemble the outflow from a well shaken bottle of champagne.

This dramatic loss of CO_2 results in the fluid becoming increasingly super-saturated as it approaches the surface. The rate of nucleation is correspondingly enhanced, so that, rather than adding only to the dimensions of existing crystals, myriads of new micro-crystals come into existence.

Hence, the change in dimension of calcite crystals at depths of a few hundred meters compared with those which form within a few meters of the surface cannot be used to indicate that the near-surface calcite has resulted from rain-water. The change in dimension of crystals is a natural result of the changes in CO_2 content as the up-welling vein-fluid approaches the surface.

In a related effect, we note that veins are commonly banded, with the infill material exhibiting this banding symmetrically arranged about a suture. In this regard, although not providing a very clear reproduction of the structure, Fig. 6 illustrates a simple two stage development around a suture. Such sutures develop in veins which grow and form at some hundred or more meters below the surface, where the rate of loss of CO_2 is slow or modest. As the period of vein development comes to a close and the last of the fluid flows up through the vein, the sutures are not completely sealed and so remain as planes of weakness. Such planes of weakness are exploited during further extension and another phase of vein development can take place and successive phases of vein development can result in a symmetry of banding in the vein.

Thicker, more complex veins, with wall-rock or mineral clasts, tend to be formed by a larger number of phases of emplacement, and show a more complex structure because of the inhomogeneity introduced by the clasts.

In near surface environments, where the grain size of the calcite crystals is microscopic, a single well-defined suture is unlikely to be developed. Fracture of the near surface veins may take place anywhere within a vein band, or more likely will form between bands or even at the junction of the vein with wall-rock. Hence, the symmetry of banding, so often seen in veins which formed at depth, will not be so clearly evident, or may not exist, in veins formed near the surface. Nevertheless, well defined banding near the surface will often be a characteristic of veins which develop from up-welling water with fluctuating physical properties.

Field Relationships Between Faults, Veins and Calcrete Deposits At Yucca Mountain

Figure 7 shows the map location and areal outline of the planned Yucca Mountain repository. Some of the major faults traversing the area are indicated (in red in the figure) and locations of some important calcrete deposits and major exposed calcite-opal veins, to be described below, are indicated as well. These "type" locations for calcite-silica surface and vein deposits have been selected from among many in the immediate area of Yucca Mountain because they are well exposed, reasonably easy to describe and, collectively, could well be regarded as definitive with respect to the mechanism of calcite-opal emplacement in this area.

Of the locations shown, those at and near the south end of Yucca Mountain are particularly important. These are indicated as "Stop 106", "106-F", "Red Cliff Gulch" and "W.W. (Wailing Wall) Fault". The sites denoted as "Stop 106" and "106-F" are at two ends of an exposure of a very extensive calcrete deposit, extending down slope from what appears to be a fault exposed at "106-F". The calcrete material at "Stop 106" was dated at 78 ka and is very thick, with about two to three meters of its thickness exposed by erosion at some points along the wash which extends south from the fault.

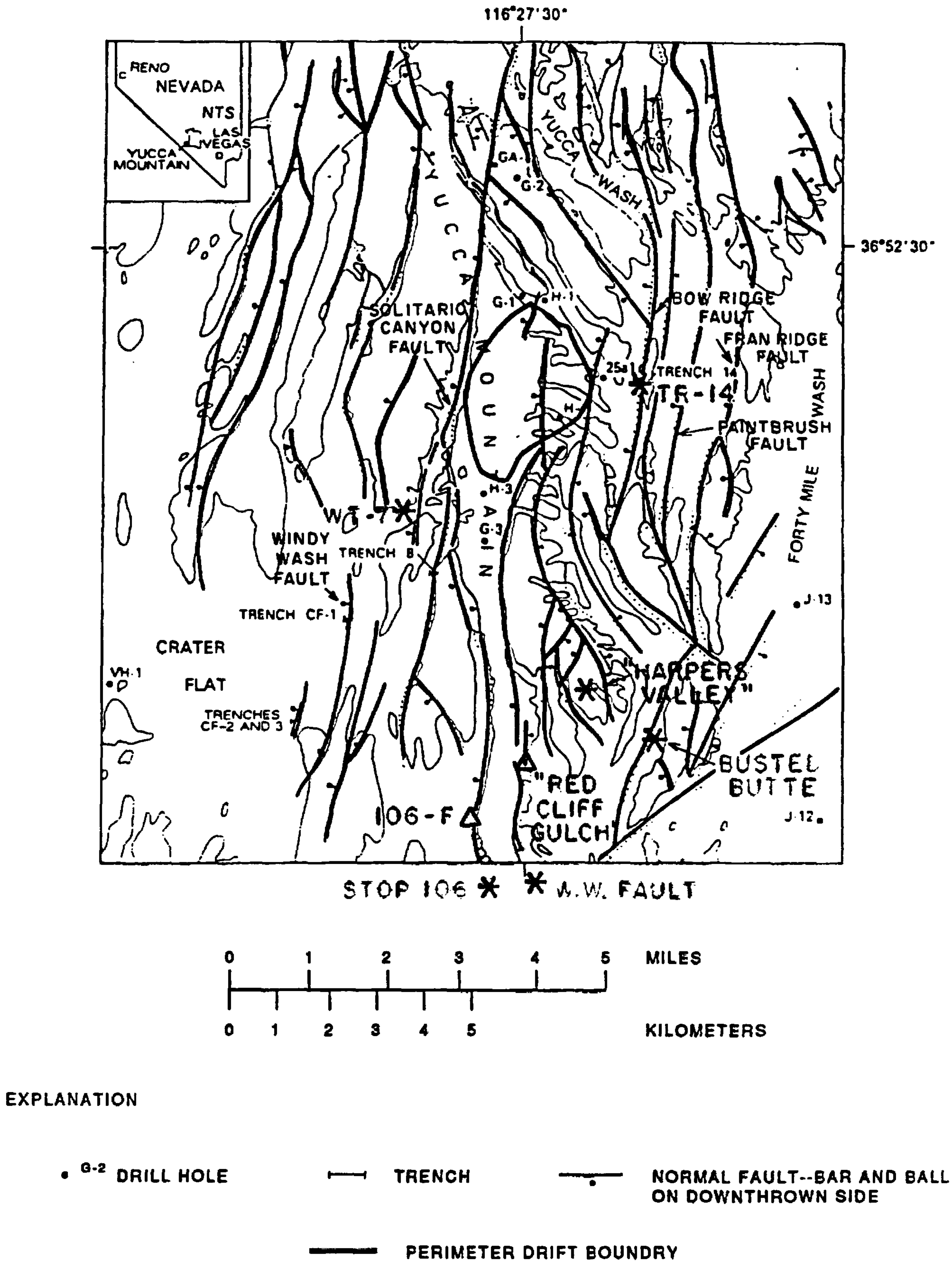
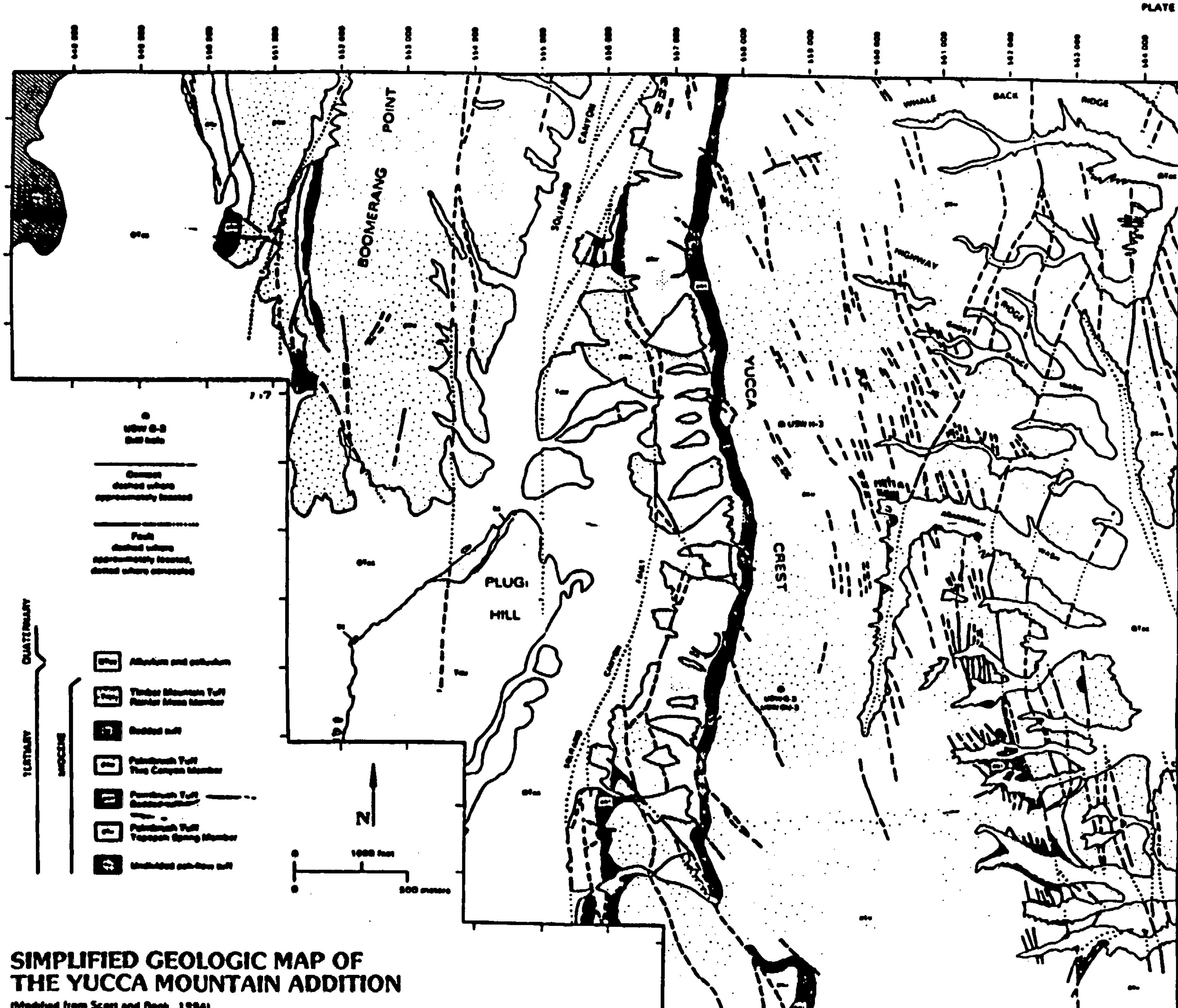


Fig. 7. - Map of Yucca Mountain and the surrounding area, showing the location of sites referenced in the text.



SIMPLIFIED GEOLOGIC MAP OF THE YUCCA MOUNTAIN ADDITION

(Modified from Scott and Bonk, 1984)

The series of photographs in Figs. 8-15, which were taken at or in the vicinity of Yucca Mountain, show examples of the characteristics of various features of the veins and calcretes and their relationship to faults, which we believe are crucial in assessing the origin of the veins and the vast majority of the calcretes exposed in the study area.

Brecciated material and vein development exposed at the south end of Yucca Mountain are shown in Figs. 8 and 9. Such brecciated veins, often with associated staining of the country rock and pedicles of alteration surrounding individual pieces of country rock included within the breccia are not uncommon in metamorphic and volcanic rocks as well as indurated sediments in many of the fold belts of the world. In the various locations around the world the ages and the temperatures of formation of these features have resulted in geologists attributing such brecciated veining and staining to hydrothermal effects. These veins, both world-wide and at Yucca Mountain, are often injected to form extension features or may be associated with faults. The close relationship of staining and faulting at Yucca Mountain is indicated in Figures 9 and 10. Here staining is almost certainly associated with hydrothermal alteration from up-welling warm or hot water along the fault.

In both of the sites seen in Figures (9.) and (10.) extensive calcretes are exposed in gullies down-slope from the faults. These faults are within a mile or two of each other as indicated in Figure 7. Relatively little calcretes are seen above either of the two faults shown here. While the fault scarp in Figure (9) is only exposed locally over about a 30 foot extent, with a steep walled gully extending down slope from it, the fault scarp in Figure (10) is exposed over a considerable distance along the side of a canyon, with numerous small gullies downslope and extending to the bottom of the canyon. The red staining of the tuff on the scarp in Figure 10 is also present in the tuffs a few feet down-slope and are exposed in the gullies below; with the

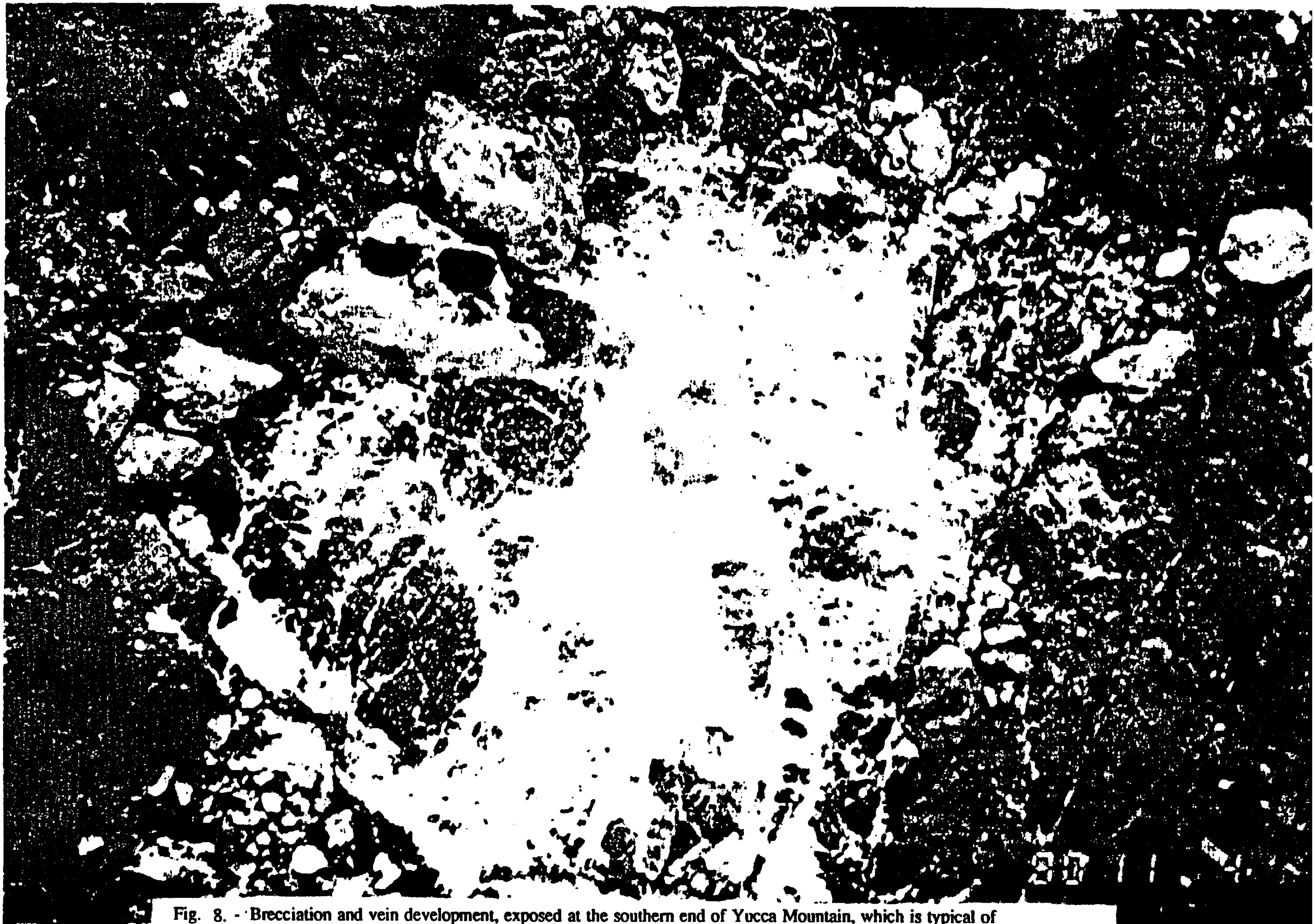


Fig. 8. - Brecciation and vein development, exposed at the southern end of Yucca Mountain, which is typical of that commonly associated with hydrothermal activity. This site is indicated as "Red Cliff Gulch" in the map in Figure 7.

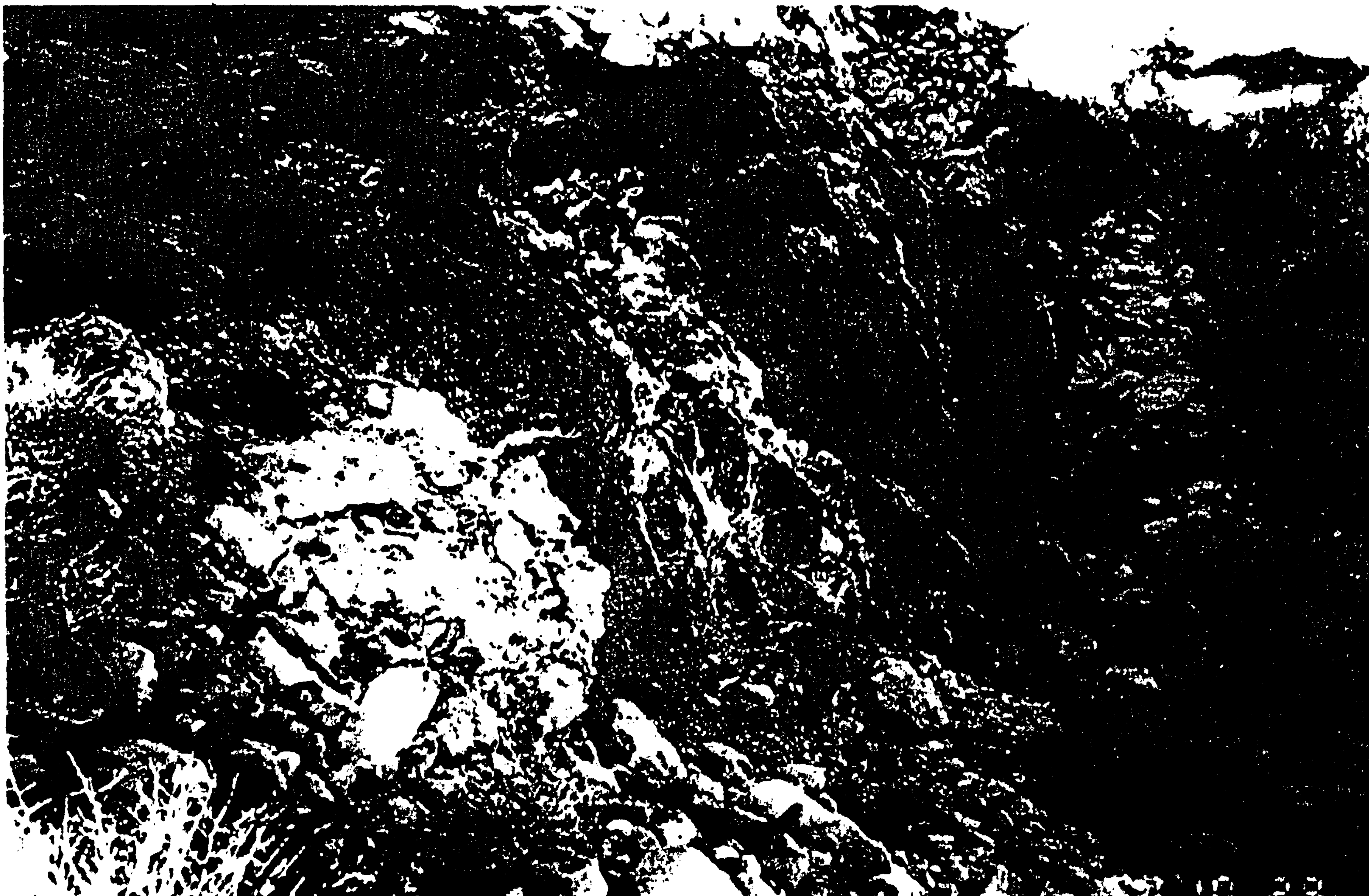


Fig. 9. - Another example of brecciation and vein development, together with staining of the surrounding rock mass. Such staining is a feature which is commonly associated with the upwelling of hot and/or chemically active hydrothermal fluids. These features are exposed in the footwall of a geologically recently formed fault scarp, one of several that can be seen in this area at the southern end of Yucca Mountain just north of "Stop 106" at the location "106-F" shown in the map in Figure 7.

color shading from red to orange-yellow.

The scarp in Figure 10 can be seen intermittently over a distance of several hundred feet along the west side of the canyon with only the northern-most section shown in the figure. As noted, calcretes are present down-slope and are exposed in the gullies with apparent thicknesses of several inches. The breccia veins shown in Figure 8 are exposed at the bottom of the canyon, some hundred feet or so below the scarp shown in Figure 10. No noticeable faulting, veins or calcretes are present on the opposite side of the canyon.

The interpretation that appears to be evident to us is that the fault in Figure 10 (actually a fault zone having some width to it) served as a fracture zone conduit for up-welling hot water which produced hydrothermal alteration in the tuff in and near the fault zone and flowed down-slope depositing calcite and silica to form the calcretes. The width of the zone of faulting and up-welling probably extended from the canyon bottom to the well defined scarp shown in Figure 10, a width of a hundred feet or so. The exposed breccias at the canyon base appear to us to indicate very energetic flows, probably involving CO_2 gas along with hot water. The breccia veins, along with considerable amounts of calcrete, are well exposed along about the half mile extent of the canyon floor indicating a large volume of flow.

Because the scarp in Figure 10 is hardly eroded and is well preserved over most of the length of the canyon, we conclude that it is a young feature. Accordingly, geologically young talus downslope from the scarp is cemented with calcite minerals clearly associated with scarp-exposed veins. However, there are no age dates available for the faulting, veins or calcretes in this area so that we do not have precise knowledge of the absolute or relative ages of these seemingly inter-related features. However, the physical evidence seems to require hydrothermal up-welling of the type described by Szymanski, with the calcretes produced by outflow along faults,

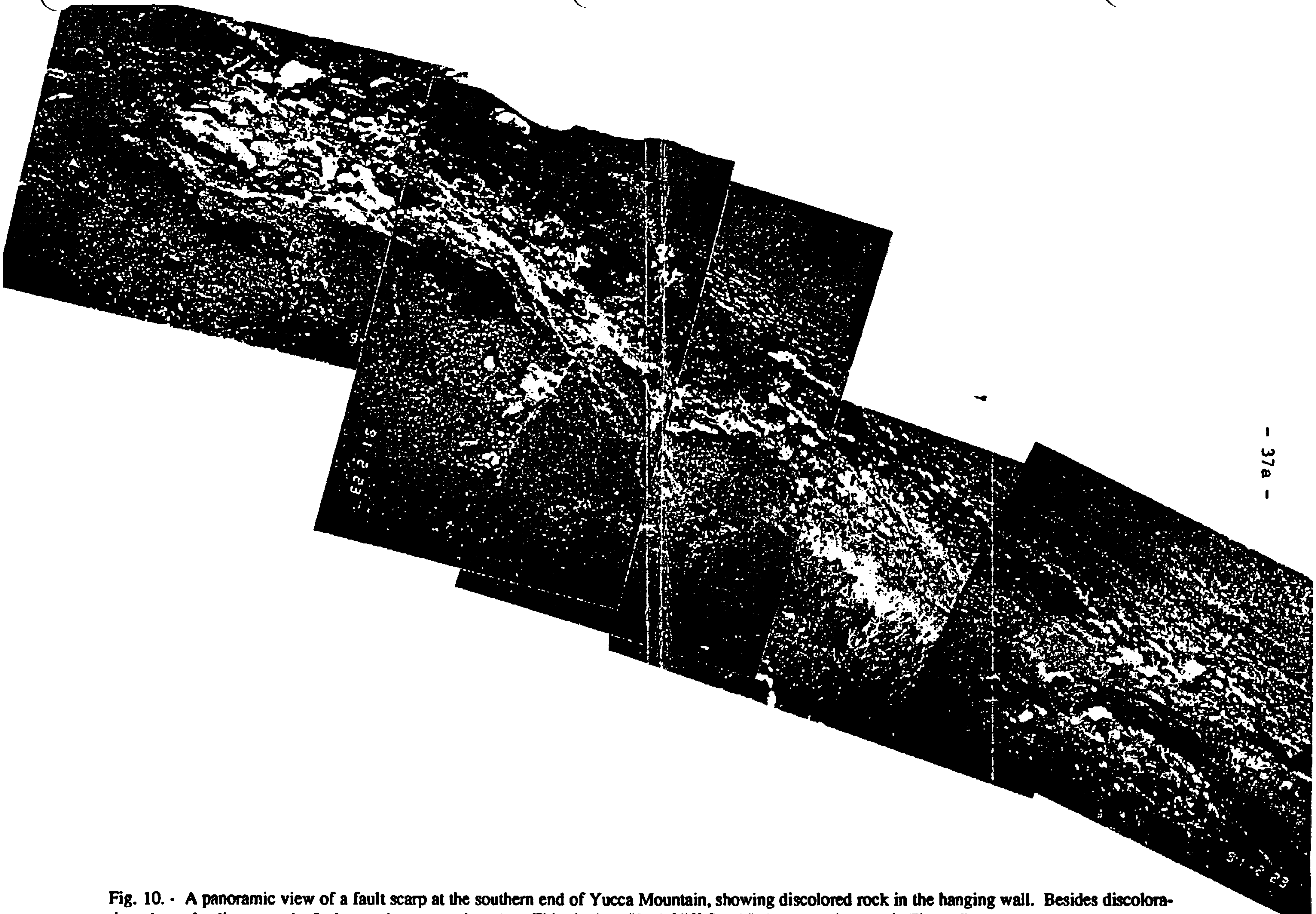


Fig. 10. - A panoramic view of a fault scarp at the southern end of Yucca Mountain, showing discolored rock in the hanging wall. Besides discoloration, the rock adjacent to the fault contains muscovite mica. This site is at "Red Cliff Gulch" shown on the map in Figure 7.

almost certainly within the Quaternary. Thus, there is good evidence that the processes described by Szymanski do take place in this area, which is at the south end of Yucca Mountain some 300 or more meters above the current water table, but we do not have a firm hold on when this activity took place, other than by the young appearance of the scarp and mineral placements shown, in part, in Figure 10.

Figure 11. shows people and a dog standing near the outcrop of rock along the fault shown in Figure 9. Evidence of the staining in Figure 9 is quickly lost as one moves upslope along the stream channel. Also, it can be seen in the foreground. It can be inferred that the thickness of calcrete associated with the cobbles is greatest along the fault line.

Such observations are completely in keeping with the interpretation that warm or hot hydrothermal fluids moved up along the fault plane. Thus, it appears that where the fault cropped out and hot fluids reached the surface, they cooled rapidly and were therefore only able to cause alteration of the country rock for a short distance on either side of the fault. We infer that when the vein-forming fluid extrudes onto the surface it tends to exhibit a high degree of super-saturation hence, as we have already noted [Fig. 4.], it is to be expected that the calcretes nearest the fault would most rapidly accumulate and that there would be a progressive reduction in thickness of the calcrete as the distance from the fault increases.

Figure 12 shows calcretes further down-slope from the stained fault zone (shown in Figure 9.) and the bank of calcite encrusted cobbles, shown in Figure 11. This photograph was taken near the site ("Stop 106") where a sample was taken and dated at 78 ka. If the interpretation of this thick calcrete bed as a deposit formed by outflow down-slope from the fault zone is representative of the age of the entire deposit, then this date suggests that up-welling along the fault has taken place quite recently. Since this site is about 300 meters above the present water

Fig. 11. - A bank of cobbles cut by the fault in Figure 9. The thickness of the calcrete associated with the cobbles is greatest along the fault line, from which it is reasonable to infer that the calcrete results from water upwelling along the fault plane. Near the feet of the people and dog, the rock is stained by hydrothermal activity (shown in Figure 9.) This staining is quickly lost as one moves upslope, into the photograph, indicating that staining, that is direct evidence of hydrothermal activity, may diminish rapidly away from a fault plane.

Fig. 12. - This figure shows a thick band of calcrete located downslope in the wash below the fault and cobbles shown in Figures (9) and (10). This site is located just north of "stop 106" where an age-date of 78,000 years has been obtained. If this age is representative, so thick a unit of calcrete could not accumulate, in the given time, by pedagenic processes relying on rainwater. Given the downslope relationship to the fault shown in Figure (9) it is reasonable to infer that these calcretes are due to outflow along the fault zone. (Other washes in this area have no exposed calcretes nor are they terminated by a fault, as is this one.)

table, then this would support Szymanski's hypothesis that up-welling from great depth is currently possible and probably likely in the future, in the event of an earthquake or volcanism.

Because of the possibility of rain-water reworking of the calcrete resulting in the appearance of younger isotopic ages, this single young age value for the calcretes cannot be viewed as necessarily representative of the true age of the deposit. Clearly much more systematic dating at various levels and locations within the calcrete zone is required for added confidence. However, if this age is indeed representative then, in our view, it is extremely unlikely that such a thickness of calcrete could have been deposited by any process other than rapid up-welling of water along the fault, followed by down-slope deposition. In particular, a pedogenic process involving rain water deposition is far too slow a process to provide such a thick accumulation in such a short time. Further, this calcrete would have to be viewed as unrelated to the fault and calcite encrusted cobbles shown in Figure 9 and 11, whereas the calcretes are exposed continuously all the way to the fault, so that such a condition strains credibility.

Other similar relationships between faulting, calcite-opal veins and calcretes occur at other sites at and adjacent to Yucca Mountain. In this regard, Figure 13 shows calcite veins and breccias in the area of the Solitario Canyon Faults on the west side of Yucca Mountain. Extensive calcretes are also present down-slope, to the west from this series of north-south trending faults (see Figure 7.). Here again the ages are not certain, but the physical evidence strongly suggests recent faulting and a causal relationship between the faults and depositions of the calcites.

Figure 14 shows a large fault scarp (the "Wailing Wall" fault) at the south end of Yucca Mountain just northeast of stop 106. This dramatic example of faulting is accompanied by calcite-silica cementing of the sand along the foot-wall of the fault. We infer that the development of slickensiding and polishing on a fault surface is evidence that, at the time these features

Fig. 13. - Evidence of hydrothermal activity can be found at many sites in the Yucca Mountain area. These views show veins and breccias which have developed adjacent to the western flank of Yucca Mountain itself, at the well site "WT-7" near the Solitario Canyon Faults shown in Figure 7.

developed, the fault surface was dry and was heated to high temperatures. However, it takes, at most, only a few seconds for the fault to move sufficiently for frictional heating to melt the rock and a correspondingly short time for the melt material to cool to form those very thin features on the fault surface.

Subsequent to the phase of polishing, ground-water, as the result of seismic pumping, is quite capable of reaching the surface along the erstwhile dry fault plane. Further, later up-welling associated with thermal convection moving upward along the fracture zone could occur. Indeed, holes dug in the sand adjacent to the fault line, as shown in Fig. 15, reveal that, close to the fault, the sand has been cemented by carbonates. Other excavations in the downthrown block, at a short distance perpendicularly away from the trend of the fault trace, show that the sand is uncemented. Thus, only along the base of the scarp is the sand cemented.

One can infer from from disposition of the cemented sands and also from the topography of the site, as shown in Figs. 14 and 15, that the most feasible source of water bearing the cementing material is from that which may well up and be transported along the fault zone.

While this fault could be relatively old, as is suggested by its limited exposure, it can serve as a conduit for up-welling water at times much later than its origin; so the cementation in the sands along the footwall could be quite recent. Indeed, the fact that loose sands are cemented at the surface would certainly imply a young age. In any case, whatever the age of the fault and the footwall cementing, in our view up-welling water along the fault is by far the most likely process and would indicate that mechanisms like those proposed by Szymanski may have been recently active and produced flows along available fault zone conduits.

The area in Figure 7 labeled "Harper's Valley", somewhat to the north of the "Wailing Wall" fault, is characterized by the exposure of numerous silica dikes and plugs intruded into

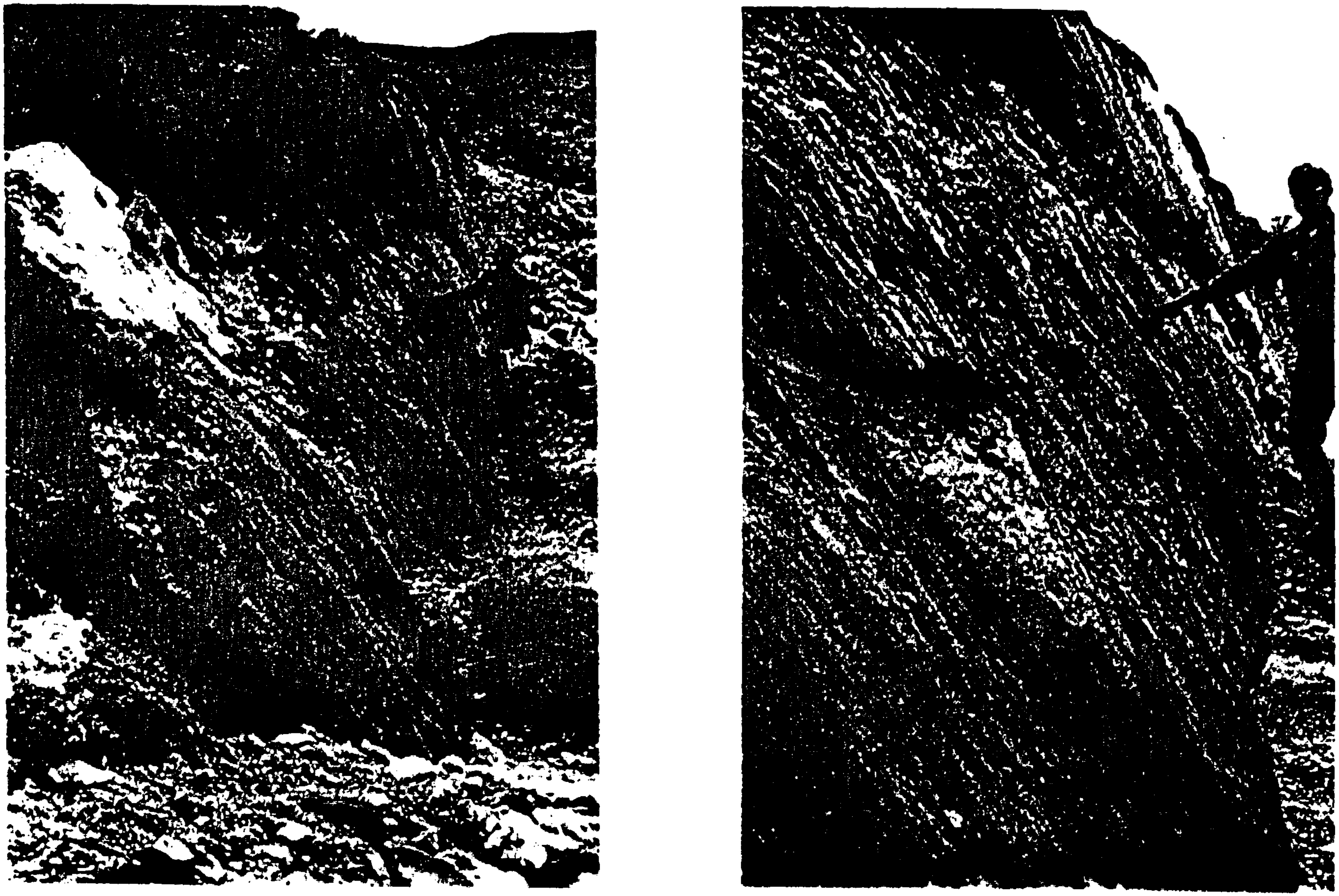


Fig. 14. - The footwall of the "Wailing Wall" Fault (W.W. Fault in Figure 7) which exhibits polished and slickensided surfaces could lead one to suspect that this structure supports the thesis that the water-table at the time of faulting was low and remained low. Certainly, when the polishing of the fault plane occurred, the rocks were dry, so that the ground-water was at some depth. However, it takes, at most, only a few tens of seconds for the frictionally heated rock to melt and them cool to form a polished veneer. Subsequently, as the result of seismic pumping, or convection, the ground water may reach the surface and produce fault, or earthquake, related mineral deposits.

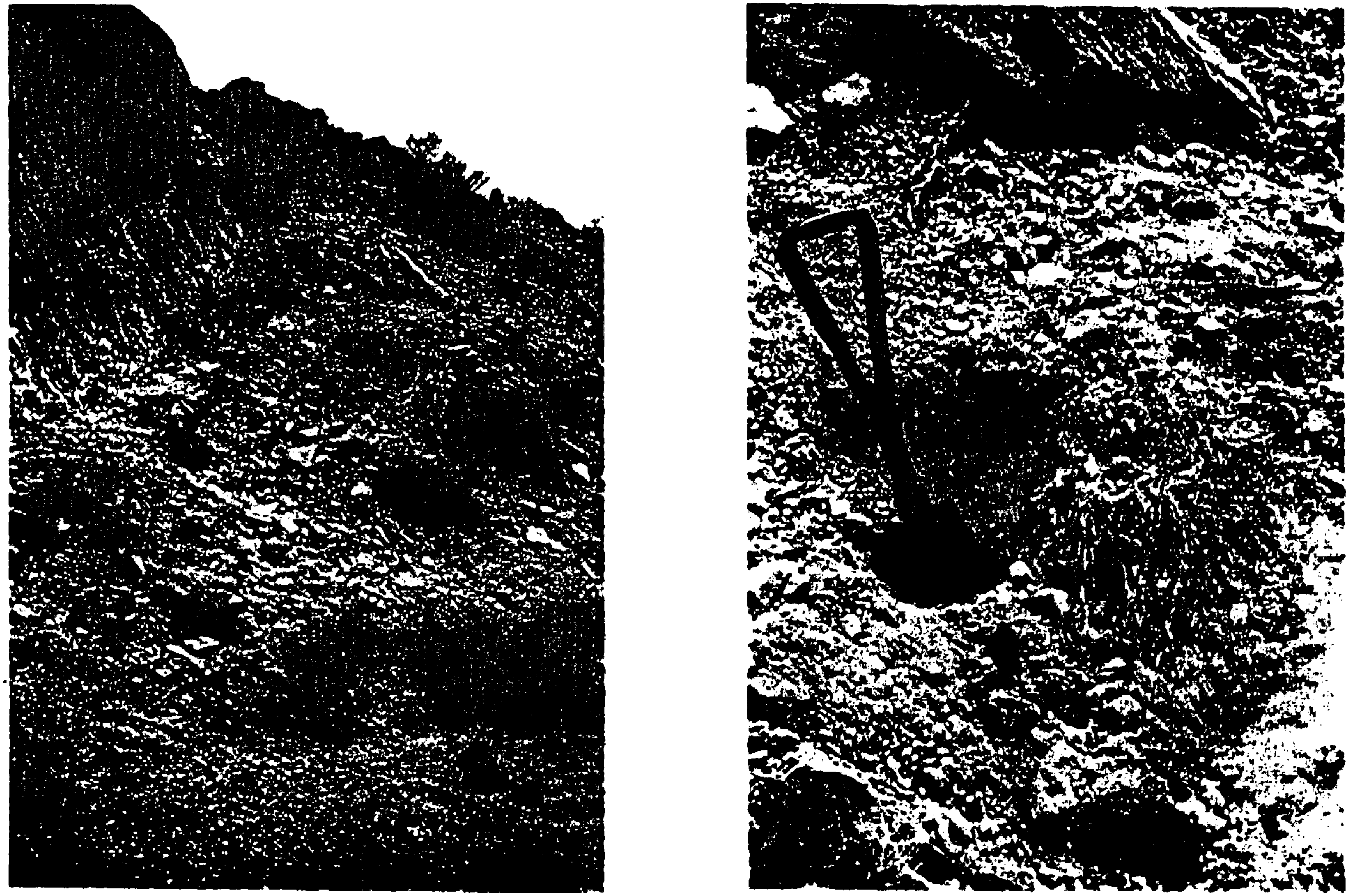


Fig. 15. - Holes dug in the sand adjacent to the fault line shown in Figure 14 reveal that, close to the fault, the sand was cemented by carbonate minerals. Away from the fault the sand is uncemented. One can infer from the topography shown in this figure and the fact that there are no similar carbonates in the vicinity that the most feasible source of water, bearing the cementing minerals, is from upwelling water transported along the fault zone.

formations with ages from just over 10 million years. The abundance of these intrusives and the strong deformation associated with them requires a very energetic mass transport source from depth. Because there is no isotopic age data available here, nor detailed mapping of which we are aware, it can only be concluded that these features are younger than the rocks in which they were emplaced; that is younger than about 10 million years. However, there is no doubt that they were emplaced after the last recognized major volcanic activity in the area. Thus, the possibility exists that they could have occurred during the early Quaternary when cones were active within Crater Flat, a few miles to the west of this site, or as recently as the last eruption at the Lathrop Wells Cone, a few miles to the south, which is estimated to have occurred only about 100 thousand years ago.

It might be argued that the deposits described and illustrated in the Figures 8-15 are of rain related pedogenic origin and have accumulated slowly and independently from any faulting, with the age date obtained at Stop 106 merely reflecting the age in an on-going process that is essentially continuous. In this case an age of 78 ka would merely reflect an age of deposition of one (recent) part of the deposit, with other sections being deposited much earlier, or it may reflect some recent reworking of an older pedogenic deposit. However, if the deposits are argued to be of such an origin, then it would require very special pleading to explain how such thick sections of calcrete are formed (as they are up-slope from "stop 106") and exposed in a gulch below a fault zone while nearly identical gulches, in the near vicinity, show little traces of calcrete.

Likewise, it is certainly difficult to explain calcretes below a fault exposed along a steep canyon wall that shows strong hydrothermal alteration along the fault zone itself and down-slope along the surface within the calcrete zone, as at "Red Cliff Gulch", while on the opposite side of the canyon there is little trace of calcretes. Surely if a rain water depositional mechanism were involved, one would expect to see calcretes exposed somewhere in the immediate vicinity other than just below the fault on the steep side of the canyon. Furthermore, pathological conditions are required to explain the cementation of talus on steep bedrock terrain as can be seen in Figure 10. Similarly, cementation of the sand only at the footwall of the "Wailing Wall Fault" is very peculiar if a rain depositional process is all that is involved since more wide-spread cementation could hardly be avoided, yet there is no evidence for it. Similar difficulties are apparent at other sites as well, such as along the Solitario Canyon Fault Zone where calcretes appear conspicuously down slope from the faults.

Our conclusion is that no satisfactory explanation of these features and observed relationships is possible using a pedogenic argument involving deposition by rain water. However, our impression is that nearly all project personnel describe surface calcite-opal deposits as pedogenic as a matter of course, issuing what amounts to an incantation upon each sighting. Questions by us, relating to the difficulties mentioned above, were often unanswered or answered by a comment to the effect that such "pedogenic deposits" are always "here and there", being controlled by subtilties of erosion and deposition, so that spatial relationships of calcretes to faults for example, are simply fortuitous. This is hardly satisfactory in view of the observations cited.

On the other hand, the existence of faulting was sometime questioned, with the fault-like scarp in Figure 9 being explained as an erosional feature while the red alteration of the tuff considered a result of heating from the deposition of overlying volcanics. If true, this would be a remarkable coincidence in itself, in that calcretes are only present in the gully down-slope from this redden tuff and have a 2 to 3 meter thickness for several hundred meters below it. Further, it seems to us that if the bed was indeed altered by heating from deposition of hot overlying

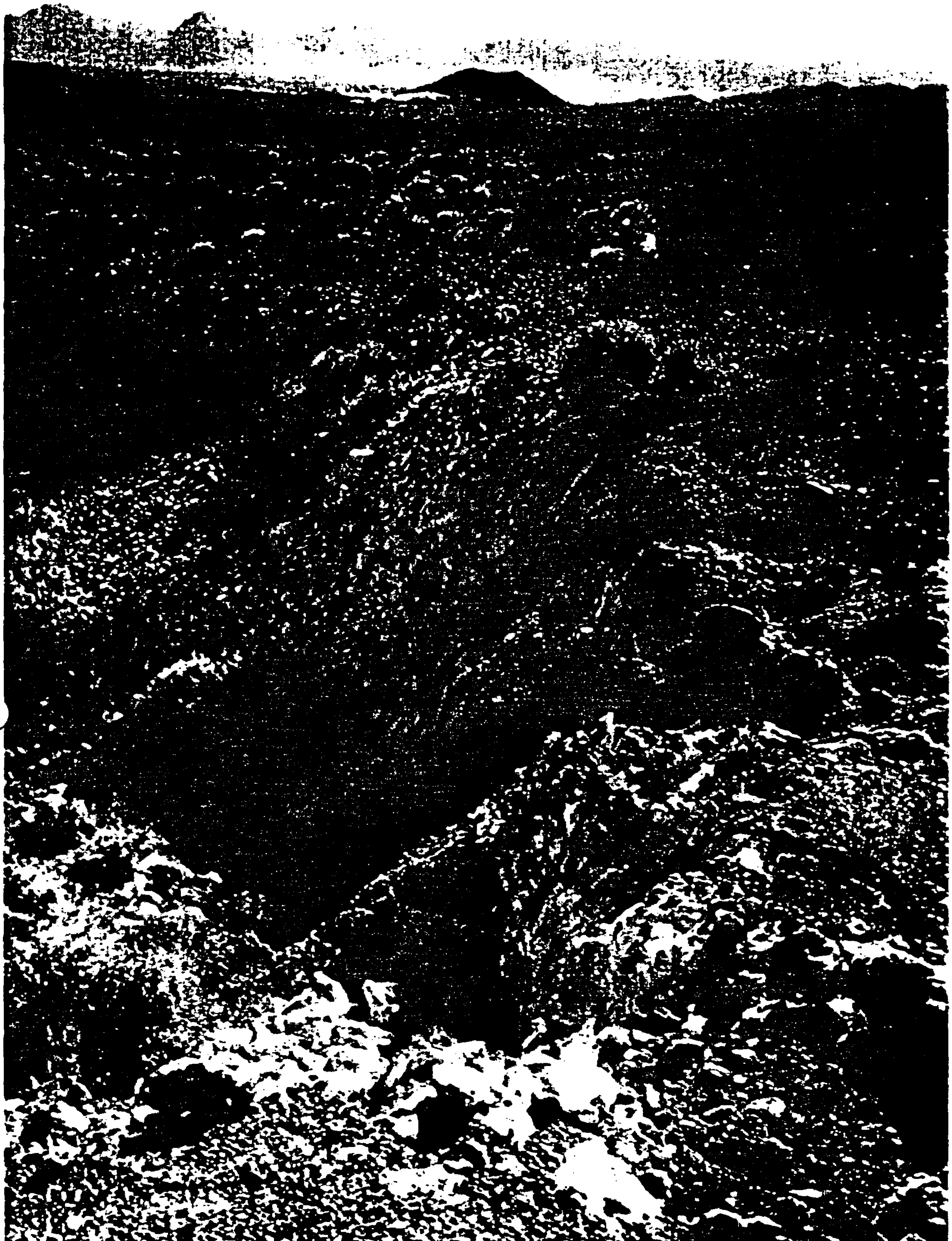


Fig.16.- A view along the scarp, of the fault shown in Fig. 9 and denoted as "106-F" on the map in Figure 7, indicating general alignment with the Lathrop Wells cinder cone. This cone is situated to the south-west of, and adjacent to, Yucca Mountain and can be seen in the background of this photo.

material, then it should have done so over a considerable area and that exposures of this reddened bed should be seen in, at least, the nearby erosional cuts. What is seen, about a mile or so away to the north, is the fault and calcretes shown in Figure 10. It is not likely that confusion could exist as to whether the scarp shown at this location is due to faulting. There, as noted earlier, the relationships of faulting, hydrothermal alteration and down-slope calcrete deposition is quite evident, even if the age is not quantitatively known.

These considerations, involving the association of features illustrated in Figures 8 through 15, appear to us to be quite straight forward evidence of up-welling along faults. As noted earlier, however, the age of these deposits is not certain, but they could be quite recent.

The origins of the deposits at the south end of Yucca Mountain could very well be connected with Crater Flat volcanism. In this regard, Figure 16. shows the orientation of the fault shown in Figure 9 relative to the volcanic cone at Lathrop Wells. The strike of the short section of the exposed scarp is in the direction of this cone, as is the strike of the "Wailing Wall" fault and the fault shown in Figure 10. A fault on the east flank of the cone, with associated calcretes and calcite coated cobbles, has this NE-SW trend as well, so that a rather wide fault zone extending from the cone to the area at the south end of Yucca Mountain is suggested. If not certain, it is at least conceivable that up-welling along various sections within such a fault zone explains the extensive carbonates seen in this area.

In this regard, two other volcanic cones at Crater Flat are shown in Figure 17. As noted in the figure caption, they occur along a NW-SE line to the Lathrop Wells Cone and it can be inferred that the volcanic activity at the surface is controlled by faults. Thus, it is probable that both the volcanism itself and associated intense convection in the water were controlled by existing fault zones in this region. Therefore, there is the possibility that the calcite-silica deposits at

Fig. 17. - The two cinder cones shown in the foreground in this figure occur to the west of, and adjacent to, Yucca Mountain. These two cones, together with the Lathrop Wells cone shown in Fig.16, occur along a straight line. It can be inferred that the development of these cones is structurally [i.e. fault] controlled. An analysis regarding the probability of future cone development that is based on the assumption that future cones will develop at random (ignoring the likelihood that emplacement of such cones will be structurally controlled) would therefore be inappropriate and misleading.

the south end of Yucca Mountain are related to the quite recent volcanic activity at the Lathrop Wells cone and involved thermally driven convection, focused upward along existing fault zones in the area, which manifested over an area mainly to the northeast of the cone. The extensive young calcite deposit on the northeast side of the cone could be another manifestation of such up-welling water closer to the cone. Most of these deposits, if associated with thermally driven up-welling, could occur at a time considerably later than the volcanic activity itself and could therefore be very recent. Alternately, some or all of the deposits could be a consequence of up-welling associated with seismic pumping and later convection due to earthquakes along faults in area, of which there are many. In either case, the evidence for up-welling seems to us to be quite strong and appears closely related to new and old faults in the area.

It should be noted that the majority of the examples shown in Figs. 8-17 are situated at the southern end of Yucca Mountain and are near, or above, the level of the proposed repository. In addition, from our analysis of the Stage Coach Road Fault complex given in Section VI, it is in this area that we expect seismic pumping to be particularly efficacious in the event of a large earthquake.

Calcite-Opal Veins and Calcretes at "Trench 14"

We now consider the structures exposed in Trench 14 and shown in Fig. 18. Many of the arguments relating to the rain-water hypothesis appear to revolve around the structures exposed here. As it was exposed, when viewed by us, the data relating to the origins of the structures in Trench 14 were not as clear-cut and unequivocal as one might wish. Without doubt, further excavation would lead to more clearly defined evidence which would enable one to reach a firmer conclusion as to the mechanism(s) involved in vein emplacement here.

At this site, as opposed to some of the others illustrated in previous figures, there is little

Fig. 18. - View of the veins and associated structures exposed in Trench 14 as seen by the authors. The location of this trench is shown in Figure 7.

obvious evidence of hydrothermal alteration of the country rock near the veins shown in Figure 18. Therefore the temperatures during deposition were low and, as estimated by various means [5], probably in the range from 15°C to 30°C. This in itself does not rule out the possibility that the veins were implaced by up-welling water. However it makes emplacement of the deposit by rain water at least a possibility.

The structures exposed in Trench 14 can be divided into three main groups of features, as follows:

1.) Three relatively thick veins can be seen which are approximately perpendicular to the topographic surface. The lower portion of the left-hand vein is, however, inclined at an apparent dip to the right of about 80° and continues as a thinner extension. Also the upper portion of the right hand vein has an apparent dip to the left of about 65°. Hence these main veins and associated smaller features occupy a fan with a downward closing angle of about 35°. All these veins exhibit marked banding.

2.) There are two main, light-cream colored "veins" which make an apparent angle of 20° to 30° with the current surface as indicated by the sky-line. (Because of perspective and irregular surfaces, the angles quoted must perforce be designated as apparent, and are merely given so that the reader can readily locate the structures in question.) The upper of these "veins" also shows some banding structure. The banding of the central of the three near-vertical veins is continued to the top of the highest, gently inclined "vein". One may infer that the top of this uppermost gently inclined "vein" was at one time the topographic surface onto which the vein-fluid extruded and then flowed downhill. The banding within the right, near-vertical vein can also be seen to extend into the gently dipping, light-cream colored layer. However, the banding emanating from the steeply dipping vein is seen to turn sharply and trend sub-parallel to the topographic surface which was extant at that time.

The lower of the gently inclined veins also exhibits evidence of banding. This banding is seen most clearly towards the left hand limit of the figure. Unfortunately, however, much of the exposed surface of this particular vein is obscured by a dark mass, with a dendritic pattern, which can probably be attributed to the root system of a plant which utilized the remnant moisture associated with the vein development. This low angle vein appears to have its origin in the left-hand, near-vertical vein, in part from the thinner spur and, at a higher level, from the main part of this left-hand vein, which sends off bands at right angles to form the gently dipping vein.

3.) The upper portion of the picture shows dark cream, or brown bands of calcite cobbles which we assume are formed by the evaporation of water on the surface, during its downhill flow.

Let us now comment on the formation of the lower gently inclined vein. In near-surface environments, such as the one in Fig. 18, the axes of principal stress will be aligned approximately normal and parallel to the topographic surface. In a region undergoing extension, the maximum principal stress, at depth, is likely to be steeply dipping. However, as the surface is approached the value of the steeply dipping (surface normal) effective stress goes to zero. It is the surface-parallel stress (in the direction of maximum slope) that is likely to become the maximum principal stress.

The magnitude of the differential stresses near the surface is, however, likely to be quite small. Hence, in a developing vein, the propagation of which is partly determined by the pressure [p] of the vein fluid, tip stresses of the developing fracture are likely not only to give rise to a fan-form fracture pattern, but also provide sufficient energy for the fracture to burst through to the topographic surface, irrespective of the magnitudes of the in-situ rock stresses.

Eventually, after several phases of emplacement (as may be inferred from the banding of the near vertical veins) the fracture becomes well sealed, while the addition of a significant amount of vein material may even enhance the magnitude of the surface-parallel principal stress. At this stage, the pressure [p] of the vein-fluid can exceed that of the body weight of the uppermost layers of rock and "float-off" the cover. The gently dipping vein, thus initiated, will reach the surface up hill from and out of frame of the exposure represented in Fig. 18. When the vein-fluid reaches the surface it will then flow downhill, lose all remaining CO_2 and also begin to evaporate, thereby depositing some or even all of the calcrete which forms the uppermost layer seen in Fig. 18.

Whereas the banding in the lower, gently-dipping unit can readily be explained by assuming up-welling water, it would require special pleading to explain these specific bands as due to rain water deposition. As we understand the hypothesis, rain-water is said to cause the more steeply dipping bands by flowing into open fissures. However, for the specific bands in question, proponents of this hypothesis would need to explain how such low angle fissures came into existence. Alternatively, if they wish to argue that these specific bands were deposited on the surface, they must explain specifically why these bands are so different in appearance from the deposits which form the dark upper portion in Fig. 18.

However, as we have already mentioned, such banding does not present a problem for an up-welling process. Veins formed at depth are commonly banded, with the infill material exhibiting this banding symmetrically arranged about a suture (see Fig. 6.) With water up-welling to the surface and depositing very fine grained material, it follows that, near the surface, such symmetry is less than perfect. Nevertheless banding, representing different phases of emplacement, is to be expected.

In order to ascertain whether rain-water deposition will result in banded veins of the type seen in Trench 14 and elsewhere in the Yucca Mountain area, it is useful to examine examples of open fractures from other areas that have been filled-in by rain derived deposits, or otherwise affected by rain water.

In this regard, fissures which currently, or in the recent past, reach the surface can be seen in certain, constrained, environments. For example, they sometimes form near the edges of the topographical high ground adjacent to some valleys, and they are to be found in extension regimes such as Iceland and, of course, in the Basin and Range Province. In these environments the reasons for the development of the fissures are different, but an examination of the type of infill, or lack of it, is instructive.

Fissures may form near the edge of a scarp, adjacent to some valleys. These are best seen when relatively strong rock, which occurs near the top of the ridge, rests upon weak mudstone or shale that dips very gently into the valley. Some such fissures, in Britain, may reach depths of at least 30-40m. The hill-top vegetation in localities where such fissures exist usually consists of grass and small bushes. The only sign of infilling these fissures exhibit is the occasional jointed block that has fallen from high in the walls of the fissure and an irregular smearing of soil and clay carried down the walls of the fissure by run-off water.

Fissures, or former fissures, in Iceland occur above thick "blind dikes", *i.e.* dikes which do not quite reach the surface. The valley floors in some parts of Iceland are covered with peat or grass. Here the fissures are frequently flooded to form water-ways. However, the water is sometimes quite shallow and reveal that the fissures are largely filled with fallen blocks of basalt. In the upland areas, the tracks of fissures are defined by gullies, again with large blocks of basalt. In some areas near the coast and in the deserts of Iceland, the blocks of basalt that fill the fissures

Fig. 19 (a) and (b) - Views of a boulder, rubble and sand filled fissure exposed to the west of and adjacent to Highway 95.

are largely covered by blown, black basaltic sand.

Many fissures in the Basin and Range are, we believe, the result of movement on listric normal faults. However, we would expect the infill of such fissures to be similar to those exhibited by the fissures in the coastal and desert areas of Iceland. Thus, the formation of the fissures will be accompanied by seismic activity and this activity is likely to cause blocks of wall-rock to fall into the fissure, especially near the topographic surface, thereby partially sealing the fissure. The near surface sealing process continues by entrapment of wind blow sand collecting between the fallen blocks. An example of what is believed to be such a sealed fissure, which occurs adjacent to Highway 95, is shown in Fig. 19a & b. We made a brief search for calcite among this infill material, but found none.

Let us now turn to the infilling of ancient fissures. We have seen a few examples where gullies, buried karst topography and old cliff sections have been infilled with later material. Such material has usually been a melange of boulders, silts and clays.

An example of infilling of a small ancient fissure is shown in Fig. 20. This fissure, in a Caledonian granite, infilled with fine material from the overlying Keuper, and was discovered when coring a quarry in the English Midlands. Three views of this core [Fig. 20] show the infilling sediments to be extremely well-bedded and, moreover, the bedding may also form in calcite deposits.

However, let us first consider the effects of rain-water on limestones. Rain-water dissolves all rock, but its effects on limestone can be particularly dramatic. In its extreme form, the direct or indirect effects of rain-water on massive limestone is to produce karst topography. Let us consider the effects of such solution on the geometry of open fractures and the characteristics of any infilling that may occur. In exposed platforms of limestone, rain-water flows down joints

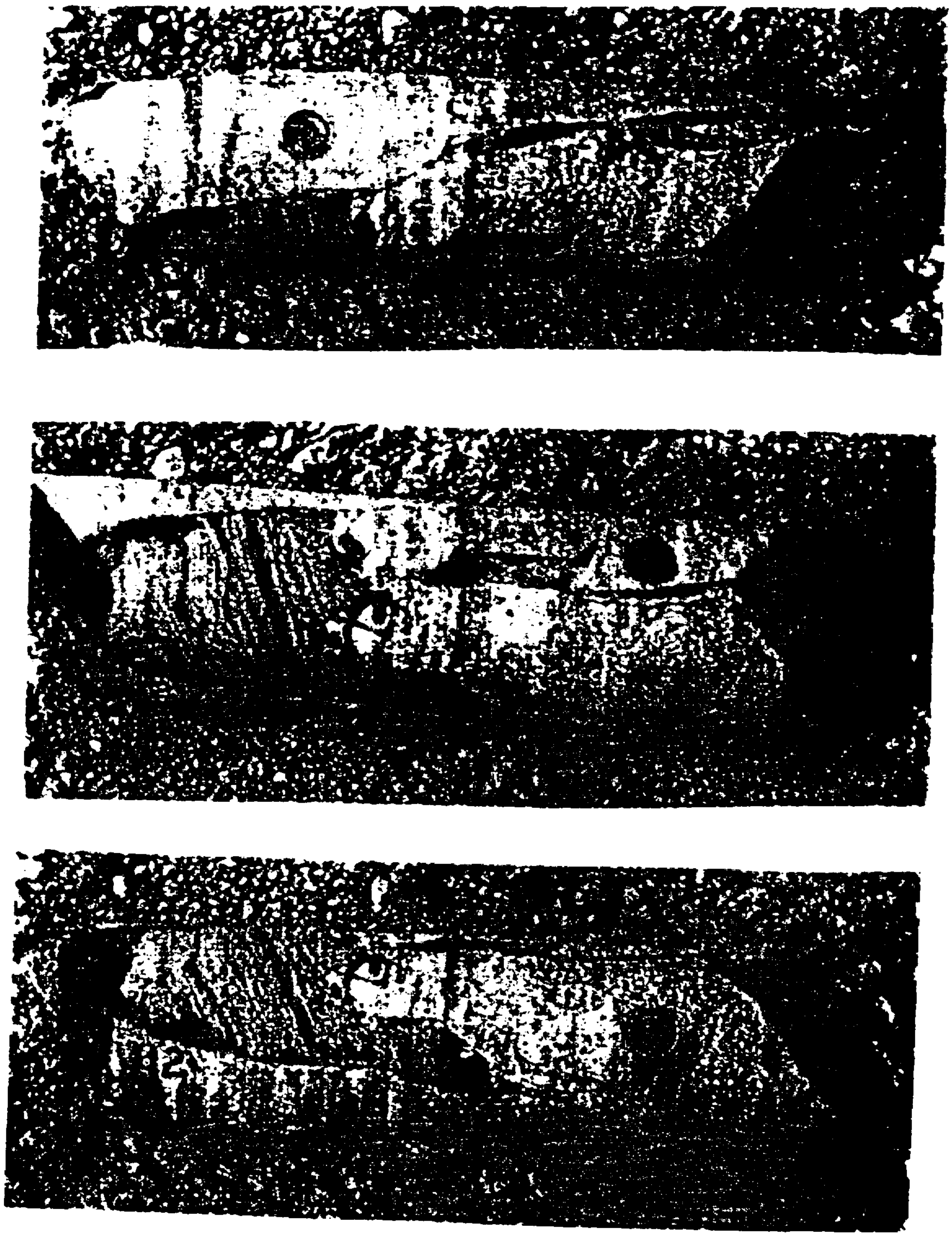


Fig. 20. - Three views of a core of granite showing the orientation of bedding in sediments which were deposited in open fissures in the granite.

and any other open fractures which intersect the topographic surface. The primary effect of the rain-water is to remove material from the topographic surface and from the walls of the fractures by solution. This process results in fractures developing a funnel-shaped profile which widens upward towards the topographic surface. Thus, deposition of calcite on the walls of such fractures, near the surface, does not occur. The influence of such solution is, of course, best seen where the rainfall is reasonably high and the rock is well exposed and not covered by soil and vegetation. This solution process will continue to operate in arid areas with low levels of rainfall, but its effects will be suitably diminished.

Of course, rain-water can eventually result in the deposition of calcite, sometimes at considerable depths below the surface. The best examples of such deposits occur in caves in massive limestones. These deposits include pendulous [and often dirty] calcretions on steep walls, stalagmites and stalagtites. Occasionally, in pools of standing water, carbonates develop horizontally bedded surfaces. These various forms of cave deposits are attributed to evaporation of water, resulting in supersaturation of the fluid which, in turn, leads to precipitation of calcite and other carbonates. An example of a fissure in limestone which is partially infilled is shown in Fig. 21. This particular feature occurs in the vicinity of Titus Canyon, Death Valley. It will be seen that the erosional surface reveals a section through the deposited calcite which ranges from pendulous lobe to horizontal bedding. We submit, therefore, that the structures represented in Figs. 19 and 20 do not in any way resemble the structures of the veins exposed in Trench 14 and in other veins seen elsewhere in the study area.

Let us now consider the effects of a period of rain, of such sufficient duration and intensity that it produces run-off in the study area. Such periods of rain will be infrequent, or even rare, but can certainly give rise to flash-floods. The rapidly flowing water soon becomes muddy and

Fig. 21.- Partially filled fissure exposed in the vicinity of Titus Canyon, Death Valley. Banding in the infilling calcite deposit shows a variety of orientations, as discussed in the text.

even capable of transporting pebbles and small boulders. Such flow will not be uniform throughout the area, but drainage will tend to concentrate on dendritic channels. If such a flow of water crosses a fissure or an open fracture it will deposit its mud, sand and pebbles into the void space. The dendritic drainage will ensure that water will mainly flow into any open fracture at points controlled by the drainâge patterns. Such material could adhere to the walls in small lobes, but is more likely to give rise to sedimentation, possibly well-bedded, of the type illustrated in Fig. 20.

However, it must be emphasised that the agent most likely to cause the infilling of open fractures, which intersect the topographic surface in desert areas, is not water, but wind. After all, the wind frequently blows strongly, while a significant rainfall may occur only rarely. This simple observation is useful in interpreting the vein deposits at Trench 14.

In this regard, within the central suture of one of the veins in Trench 14, a thin deposit of ash can be seen. This was almost certainly introduced by wind action at a time when the suture had been opened by regional extension. However, it would not cause us any concern if the ash were introduced from water run-off, because the important point is that the ash is not cemented. This is an important observation that mitigates against a pedogenic origin for the calcite-opal veins in Trench 14. Specifically, the ash presumably filled a narrow fissure that had developed in a vein in Trench 14 during the activity of one of the near-by spatter cones, some many tens of thousands of years ago. If efficient deposition of calcite and opal by rain-water occurs to give the vein formation, then, by its very nature, it should occur throughout the time span after the deposition of the ash, so that the ash should be cemented - but it is not. Conversely, the presence of uncemented ash in the vein is not a problem if episodic up-welling water is the source of the vein minerals. One would merely conclude that there has been no up-welling fluid which has passed through that particular vein since the emplacement of the ash.

We observe that all the evidence we have adduced and illustrated in relation to Trench 14 is entirely consistent with the traditional way of interpreting veins as practiced by almost all geologists. This logical approach results in specific interpretations that are consistent with Szymanski's model. We submit that this interpretation is not only the simplest, but appears to be the only one that provides a self consistent explanation of the observations.

Calcite-Opal Veins at Depth at Yucca Mountain

Assuming high concentrations of silica and calcium in rain water at the surface there will certainly be deposition of opal and calcium carbonates along surfaces where evaporation occurs. This process can accumulate such minerals on the surface and can also fill cracks and faults into which the water can flow. However, this is a very slow depositional process and open fractures and faults will rapidly fill with local rock fragments due to erosional processes before such a process can accumulate any appreciable mineral volumes along fracture walls. This debris filling will be particularly active near the surface, where such local material will enter the fracture most rapidly. In this case the water still enters the fracture zone and moves down, but now by seepage in a permeable fragmented medium with narrow void spaces and high solid surface area exposed to wetting. In this case the water moves downward slowly and mineral deposition will be efficient near the surface, where evaporation will occur along the large total surface area presented by the fragments. This process of mineral deposition will therefore tend to rapidly seal the fracture zones at the earths surface and the higher the concentrations of calcium and silica in the water the faster the sealing will take place.

At this stage rain water would not be able to penetrate the fracture or fault zone. Consequently the only deposition of minerals by this mechanism will be in the zone close to the surface - probably only to depths of a few meters. Further, the texture of the calcite-opal material filling this upper-most zone of a fault or fracture would be characterized by fragments of country rock in contact with each other, with "pockets" of calcite-opal having no well developed continuous banded texture. That is, the zone would be a rather heterogeneous mix of small and large fragments of country rock and discontinuous and thinly layered calcite and opal. This process, therefore, is very unlikely to account for the calcite-opal veins at great depths in Yucca Mountain and does not appear to be consistent with the near surface veins in faults that are observed to have thick vertical bands of nearly pure calcite alternating with similar bands of opal, usually enclosing relatively large "floating" fragments of Tuff. On the other hand, a rapid process of up-welling of mineral rich fluids could be expected to produce such veins, both at the surface and at depth.

The existence of calcite-opal veins at depth at Yucca Mountain, throughout the unsaturated zone and within the saturated zone to the deepest points penetrated is by itself, evidence supporting the hypothesis of upward moving calcium rich water deposition from the limestone formations at depth. Figure 22a, b, c shows sections of drill core from the bore hole USW-GU3 located, as shown in Figure 7-b, near the south end of the proposed repository at Yucca Mountain. Rather thick veins of calcite occur in Figures 22a and b, while in 22c thin veins are present at many locations. The tuff is clearly altered and stained both above and below the large vein in Figure 22a so that hydrothermal deposition is indicated. Fluid inclusions are observed in the vein material and homogenization-temperature determinations [39] indicate emplacement in the range from 100°C to 200°C. Therefore, at least some veins at depth are of considerable width and appear to be associated with hot up-welling water deposition. These examples are indicative of the calcite veins encountered throughout the roughly 1 km depth range explored at several sites at Yucca Mountain and, in our judgement, clearly require up-welling water as the

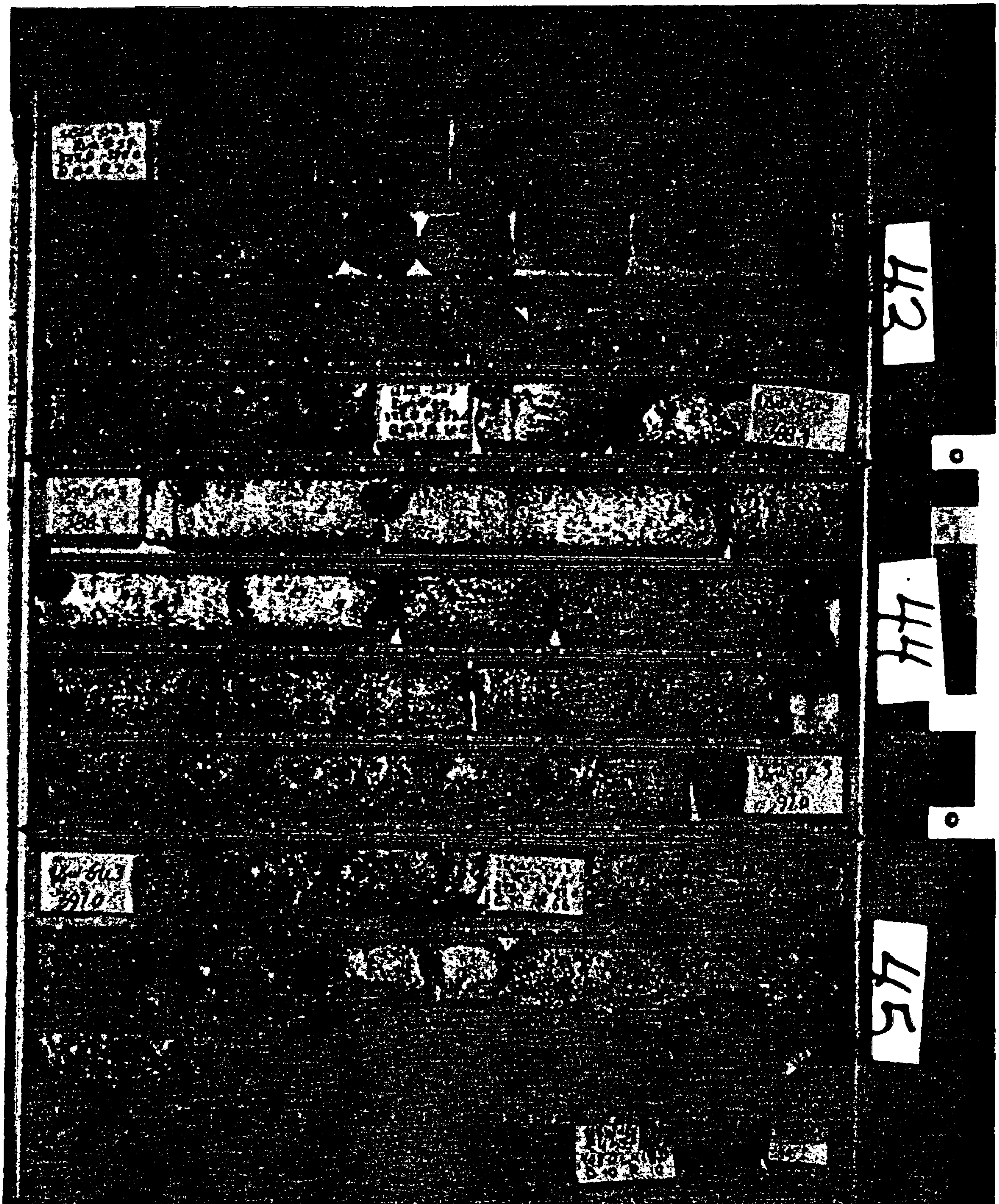


Fig. 22a. - Core samples from the drill hole USW-GU3 in the depth range from about 380 to 420 ft. below the surface. About a four foot wide calcite vein is encountered at around 385 ft. The tuff is also locally altered on either side of the vein.

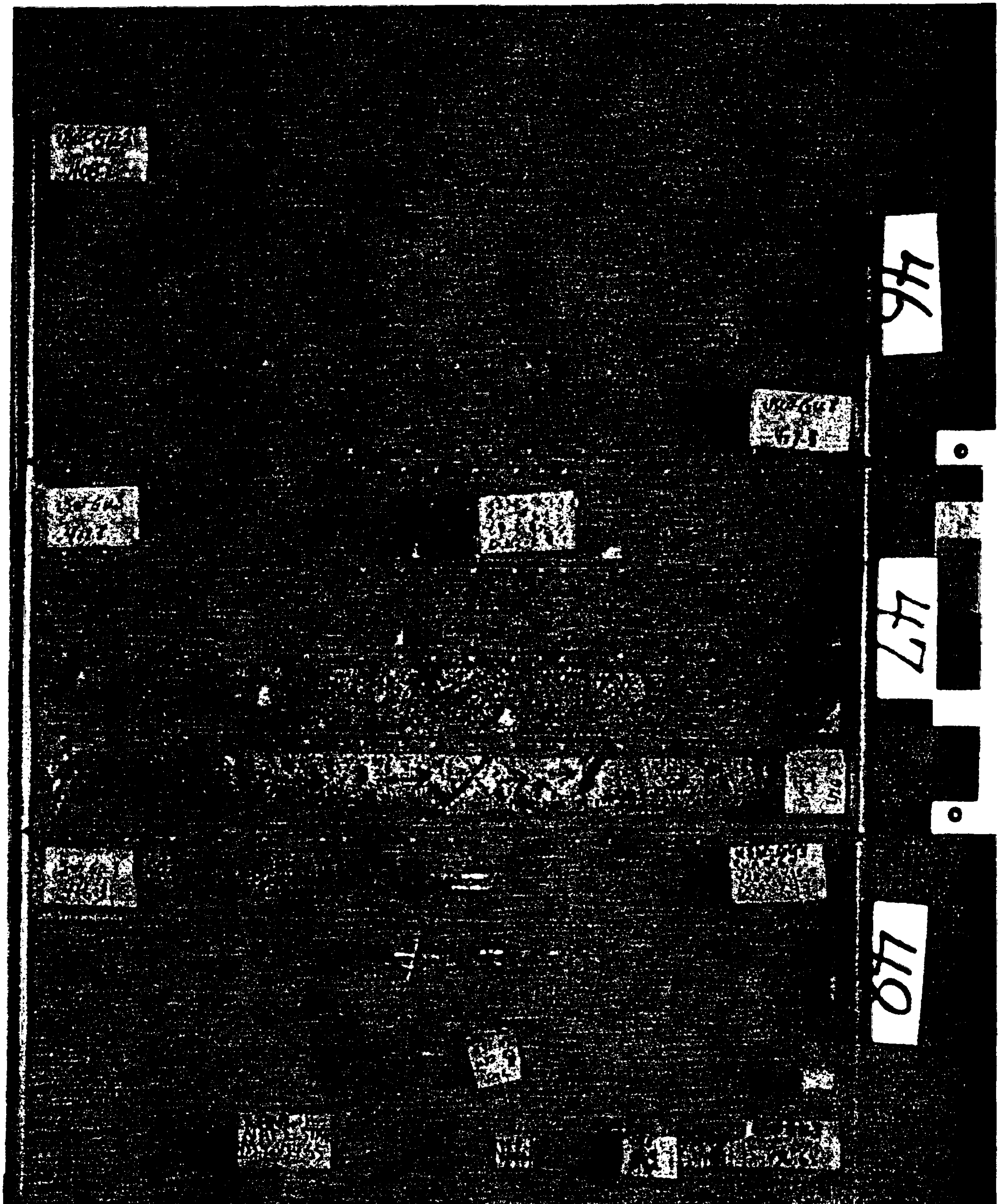


Fig. 22b. - Core samples from the drill hole USW-GU3 in the depth range from about 410 to 435 ft. below the surface. A four to five foot calcite vein is encountered at about 420 ft. and the tuff is also altered local to the vein.

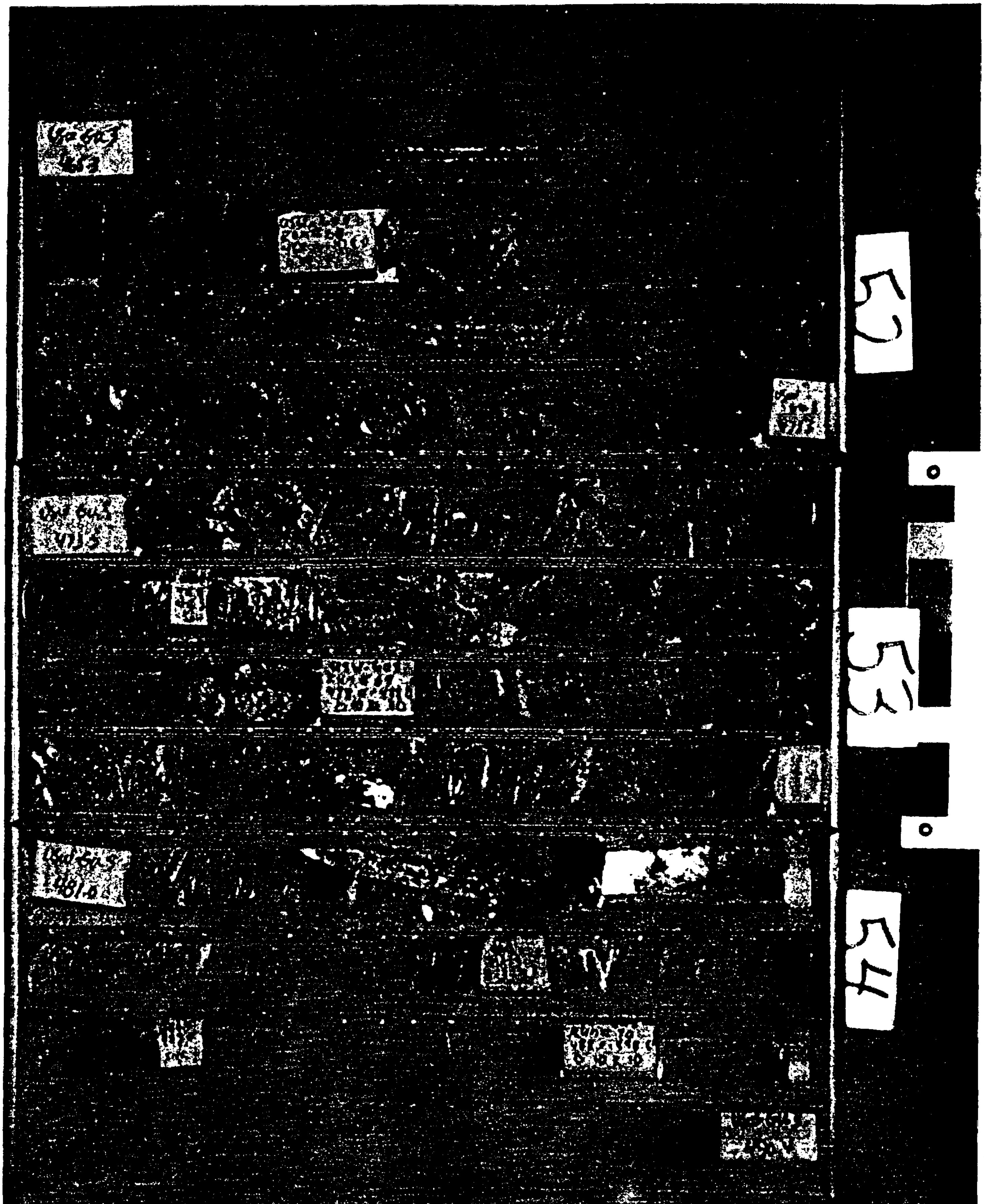


Fig. 22c. - Core samples from the drill holes USW-GU3 in the depth range from about 465 to 490 ft. below the surface. Numerous thin veins of calcite are encountered in this range.

depositional mechanism.

The ages of these veins are critical, since if they are old then they could have originated during an early active volcanic phase when water convection from depth would have been likely. But, in this regard, the ages obtained for vein calcites at depth are quite recent, ranging from about 25 ka to 500 ka, as reported by Szabo and Kyser [11], [12], Szabo et al. [13]. If these dates are accurate and represent the true ages for the veins, then it would certainly be probable that up-welling occurred recently and had produced fracture filling all the way to the surface.

On the other hand, if the isotopic ages are unreliable or could have been altered by reworking from infiltrating meteoric water, then the situation is less certain. Obviously the true ages would have to be very much older than measured in order to correspond to the last major volcanic activity of about ten million years ago, and it doesn't seem likely that a straightforward age measurement error of such magnitude has occurred. What might be considered plausible, under the pedogenic model hypothesis, is reworking by rain water. However, we find this possibility less than compelling since, taken in its entirely, the infiltrating rain water processes would have to simultaneously deposit the abundant vein fillings and calcites seen at the surface and as well, result in the dissolution and redeposition of calcite and silica at great depth.

First of all, if the process of deposition at the surface is efficient enough to produce the observed surface deposits then, as described earlier, it would surely seal the surface and make it difficult for such run-off to infiltrate to depth in any wide spread manner throughout the area of the mountain. On the other hand, if the pedogenic processes are not really very efficient, as we in fact believe, then they may not seal off the deep zone and so some reworking is possible. However, now it is difficult, if not impossible, for such a process to produce the veins and calcretes at the surface in the volumes observed. Therefore, the pedogenic model cannot simultaneously explain both the surface calcite-opal deposits and the calcite veins at depth.

Therefore, the evidence of calcite veins at depth produces a problem for any pedogenic model since it is difficult, at best, to simultaneously explain both the extensive surface deposits and these deep veins, regardless of the ages of the vein deposits. Given the current open fracture system at Yucca Mountain with probable rapid rain water drainage to the water table in at least some areas at the site, the interpretation that does seem plausible to us is that both the surface veins and those encountered by drilling at depth are due to up-welling water and that there has been some re-working, resulting in altered ages for the deposits. Such reworking would be expected to be localized and erratic so that at least some, if not many, of the ages obtained for the vein material would reflect true ages of deposition. Consequently, the likelihood is, in our view, that the veins are relatively young (much younger than can be attributed to the volcanism at 10 ma) and are associated with up-welling water from depth. Additional age dates, using a variety of methods, would of course be necessary to produce a very confident estimate of the frequency of such occurrences, but we see little possibility that all these veins could be much older than the ages already obtained.

Calcite Veins and Calcretes in Sand Ramps at Busted Butte

Another difficulty encountered by a pedogenic model and the reliance on rain water deposition of calcite and opal veins is the emplacement of veins in the sand-ramps which occur in the vicinity of Trench 14 and elsewhere in the study area. In this regard, sand ramps occur on both the east and west flanks of Busted Butte and hydrogenic deposits are found 400 m. above the current water-table. Figures 23a and 23b illustrate the ramps and deposits on the west side of Busted Butte [37]. Several (typically three) calcrete layers, each about one meter thick are exposed, usually in erosional channels within the sand-ramps, as in Figure 23b. These layers are

Figure 23a View of western flank of Busted Butte from southern Yucca Mountain. Sand ramps contain erosional channels at mid-height in the photo.

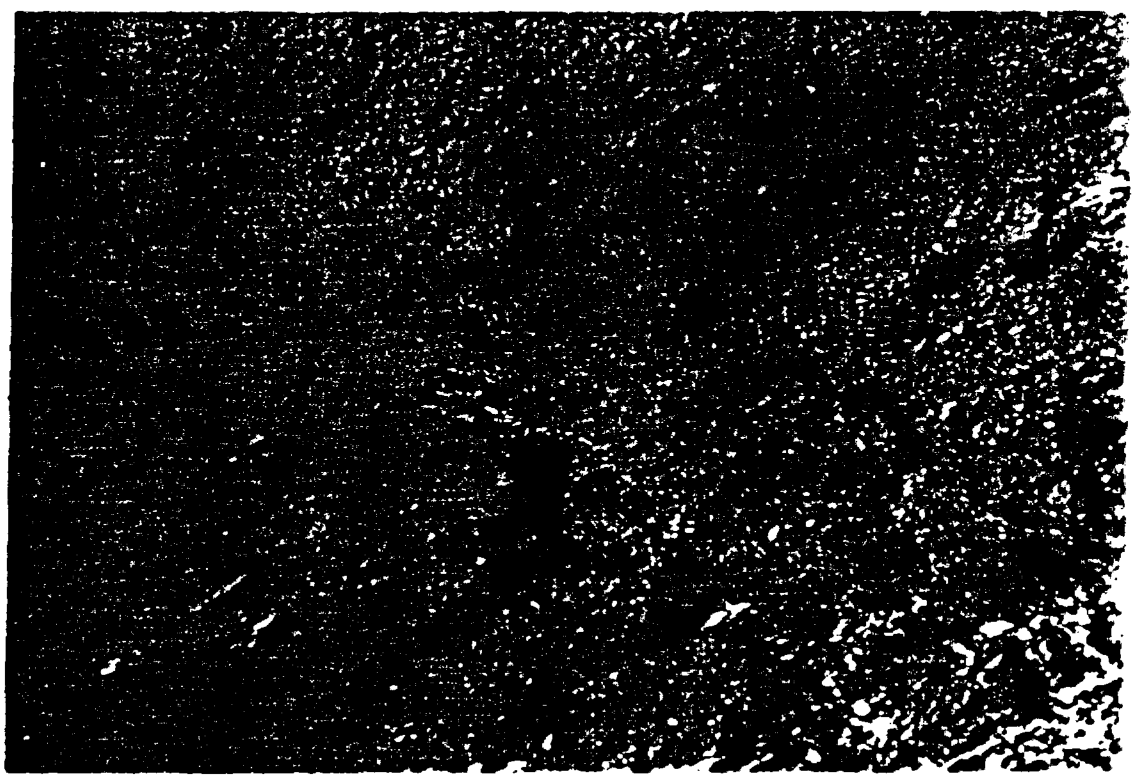


Figure 23b Calcrete layer exposed in an erosional channel of the sand ramps on the western flank of Busted Butte.

parallel to the slope of the ramp and presumably indicate different surface levels at different stages in the accretion of the sand-ramp.

Near-vertical veins are also exposed on the steep slopes flanking the erosional channels. On the western flank of Busted Butte the veins are thin, of the order of a few centimeters. On the eastern flank veins are exposed that exceed 20 cm. in thickness and can be traced for a vertical distance of about 10 m. Comparable vertical veins are also exposed in the bed-rock where the drainage channels reach the base of the sand-ramp.

In order to evaluate the potential of the Pedogenic Model as a means of explaining the occurrence of these veins, consider for the moment the hypothesis that the inclined calcrete sheets in the sand-ramps are the result of deposition by rainwater. These inclined sheets will form a carapace which tends to shed water from the ramp, so that rain-water penetration into the sand below the calcrete layer will be minimal. Hence, the sand ramp will be essentially dry. Consequently, any vertical free-standing surface i.e., vertical fractures, cannot be sustained in such material for long since caving and filling would be very rapid. (At a more pragmatic level, one need only construct the Mohr's envelope for sand to realize that in a large sand mass, failure can only take place by shear, so that this kind of analysis also indicates that such a material cannot sustain an open fracture.) Therefore, the very presence of such planar vertical veins automatically rules out a pedogenic rain-water depositional origin for these vertical veins.

The next question is whether these vertical veins can be explained in terms of rapidly upwelling waters emanating from great depth, as would occur in the hydro-tectonic model. In this regard we have observed, at Tecopa Hot Springs, CA. located about 100 km south of Yucca Mountain, spring water issuing from the summit of a sand mound which stands about 2m. above the surrounding land level. When considering such a small feature, it is easy to envisage that

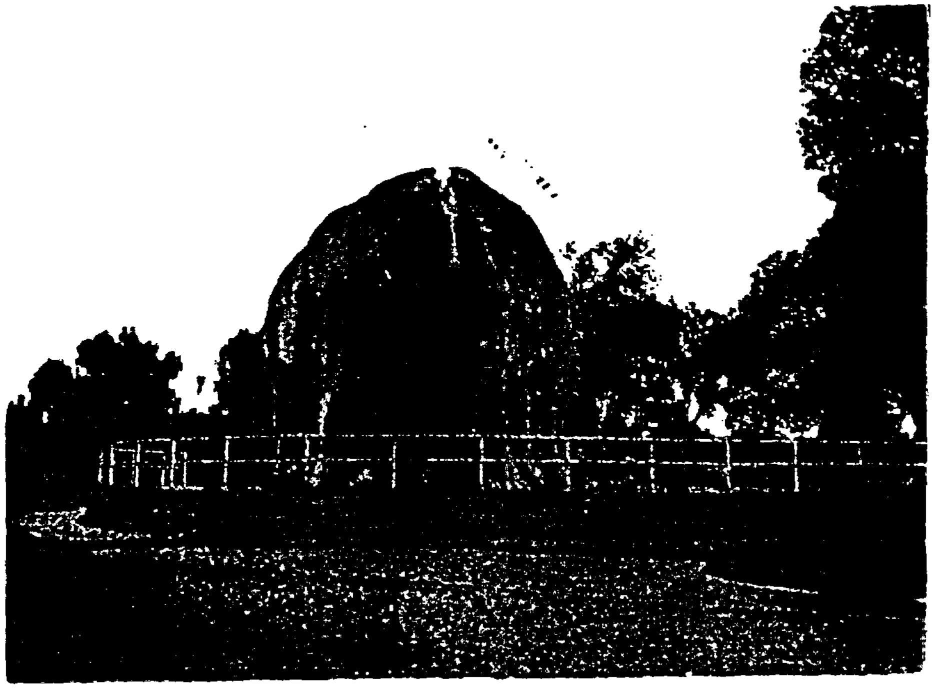


Figure 24a Discharges of mineralized spring waters sometimes form ascending orifices, as illustrated in Thermopolis, WY.

Figure 24b Spring discharges into (paleo) lakes sometimes form tall spires of calcium carbonate, as illustrated at Mono Lake, CA.

up-welling spring-water, saturated in calcium carbonate, will precipitate calcite in the sand, first at the base in the immediate vicinity of the spring orifice beneath the sand. Then as this precipitate prevents easy lateral migration of the up-welling water, precipitation is forced to occur higher and higher, until eventually the spring is forced to flow out at the top of the sand body. We therefore conclude that a similar mechanism has operated within the sand-ramps to form the observed veins. Indeed, Figures 24(a) and (b) demonstrate that this process can operate even when the spring water wells up into the air.

In view of the probable origins of the sand ramp veins, it is also clearly appropriate to consider whether the calcretes within the sand-ramp can be the result of rain-water deposition. Proponents of the rain-water hypothesis explain the generation of calcrete in terms of wind-borne dust which contains calcite. This calcite is dissolved in rain-water and then, sometime after some degree of transport and concentration by drainage, develops as sheets of calcrete. The obvious questions that present themselves are:

1.) If these layers of calcrete are the result of rain-water, why are they discrete and why is the process in the sand-ramps not a near continuous one, interrupted only by the periods of drought?

2.) Calcite-bearing dust will be blown everywhere in the vicinity of Yucca Mountain. Rain, when it occurs will fall over reasonably wide areas. Why then, are areas of surficial calcrete commonly associated with areas downslope from faults within which vein development is known to occur?

On the other hand, there are areas where, because the exposure is extremely good, calcretes are known not to exist; for example in the cinder cone at Lathrop Wells shown in Fig. 25. Here, however, wind-blown dust occurs and it sometimes rains, yet calcrete development is conspicuous by its absence throughout the excavated section of the structure. Surely, if the process were

Fig. 25. - A view showing mining excavations into the Lathrop Wells cinder cone. In these fresh exposures there is clear evidence of ancient wind-blown dust, but there is no evidence of the development of hydrogenic calcretes or of veins.

a significant source for calcrete deposition in this area over the last several million years, one would expect some sign of it here.

Of course, calcrete pediments are observed to occur where no veins are apparent. We would argue that trenching and other forms of investigation would often demonstrate that veins associated with faults underlaid these pediments, or that a fault zone with veining existed up slope from such pediments. Needless to say, however, it is not a part of our thesis that calcrete deposits can not result from rain-water. We merely conclude that such deposits represent a very small proportion of the total amount of calcrete seen on and around Yucca Mountain.

Depositional Rates and Ages of Calcite Deposits

Beyond the considerations of the simple mechanical aspects of rain water deposition of calcites versus those up-welling water, it is important to consider quantitative aspects of these processes. It has been observed [41] that, in the vicinity of Yucca Mountain, wind transports and deposits dust and sand at a rate of between 15-30g/ m^2 /year. Of this, perhaps 15 percent is composed of calcite. Rain could dissolve the calcite, along with other mineral species. When the surface water then infiltrates the surface layers and evaporates, one would expect that most of the dissolved minerals would be precipitated within about 1 m. of the surface. If we make the assumption (favorable to the rain water hypothesis) that occasional large influxes of flood water do not remove a significant proportion of the calcite accumulation so formed; then, over some specific period, slope-parallel layers of calcrete could develop.

To form a 1 m. thick calcrete deposit, many tens of meters of wind blown dust need to have been leached of calcite; the remaining dust must then be blown away. However, the supply of both surface moisture and of wind-blown dust is severely limited. The average rainfall for the area for the last million years is likely to have been close to 15 cm/yr, and the supply of wind blown calcite has been about 3gm/m^2/yr for the past several years [41]. Infiltrating rainwater can only be expected to reach levels of saturation of $CaCO_3$ of about 10 ppm. Even if we assume that solution/redeposition process is 100 percent efficient†, it requires at least one and possibly several million years to produce a 1 m. thick layer of calcrete by this process. Notably, this bounding rate is comparable with the maximum rate of growth for calcretes throughout the Southwestern U.S. [10].

In this regard, conditions at Busted Butte appear unsuited for achieving maximum average rates of dust accumulation in the Southwester U.S. , yet meter thick units of layer-parallel calcrete have formed in about one tenth of the time, i.e. 10^5 yrs., if we accept dates given for these deposits as representative. In this case the rates of deposition by rain water would be too low by at least an order of magnitude to explain the volumes accumulated and their ages.

Another striking observation in veins is the frequently observed association of quantities of opaline silica within dominantly calcite veins. In the Pedogenic Model, the rain-water that is supposed to form a specific vein does not materially change its average composition over a period of a million years or so. Similarly the rocks over, or through, which the rain-water flows remain the same. A mechanism by which evaporative rain-water deposition can explain the juxtaposition of near pure, wide bands of completely different mineral species within the same vein has not been discussed in any detail to our knowledge. However, our own analysis leads us to expect that the Pedogenic Model, at best, can only provide traces of opal with no very clear banding.

However, a juxtaposition of calcite and opal is possible or even likely in terms of the conventional theory of vein emplacement by up-welling water and is commonly observed in

† Anyone who witnessed the flash-flooding of down-town Las Vegas on June 10th, 1990, will be convinced that the proposed system of calcrete accumulation is far from 100 per cent efficient.

association with contemporary springs in the region. In this regard, a fundamental aspect of the Szymanski model is the important influence of periodic cycles of convection. These convection cells are not expected or likely to be constant in space or time. Therefore, in this model it is reasonable to expect that up-welling waters emanating from different source areas may, from time to time, change their dominant mineral in solution from calcites to silica.

It has also been noted that the solubility of silica, at temperatures of less than 150° C, is low. In order that silica may be brought to the surface in the concentrations required, one would require a rather rapid up-welling of fluid from considerable depth. Such rapid up-welling of high temperature fluids is likely to occur relatively infrequently. The fact that the silica veins and bands are usually relatively sparse (but well developed and pure) could be taken as testimony for this "infrequency".

The Mode of Emplacement of Veins at Yucca Mountain: A Summary of Principal Problems for a Pedogenic Model Origin

We have considered at some length two methods of vein emplacement. These are:

1.) The conventional theory of vein development which relates the formation of these structures to the upward flow of saturated fluids through fractures, which also can result in extensive surface deposits of calcite and/or silica when the fluids are extruded on the surface.

2.) The rain-water/pedogenic hypothesis of vein formation.

As regards the first of these alternatives, we can state with confidence that we have not observed a single feature or manifestation associated with vein development in the Yucca Mountain area that we have not been able to explain in terms of the conventional up-welling theory of vein formation.

As the reader will appreciate, we cannot make a comparable statement regarding the rain-water/pedogenic hypothesis. Indeed, we have indicated in the preceding section, a number of fundamental criticisms that we consider prohibit the application of this model to vein emplacement at Yucca Mountain. These criticisms include the following:

1.) Calcite veins observed in cores at depths of hundreds of meters at Yucca Mountain are difficult if not impossible to explain as descending rain water deposits. Some of these veins have young isotopic ages (25 to 50 ka) and the cores also indicate hydrothermal alteration of the surrounding tuff. The likelihood of altered ages by reworking is minimal at these depths, so that these are, most probably, relatively recent hot-water vein deposits. This is a particularly critical problem, for there is no point in supporting the rain-water hypothesis if it is considered to account for only the vein material in the top few tens or meters. To be of any use in lending support to a stable water-table argument, the rain-water hypothesis must be held capable of causing veins to develop at depths down to a kilometer or more.

2.) Features we have noted in surface exposed veins and which we feel cannot be explained in terms of the rain-water hypothesis include:

- The marked difference in internal structures between veins, which we claim are the result of up-welling fluids, and fissures that are known to have been infilled from above.
- The increase in grain-size of calcite crystals from the surface downward.
- The juxtaposition of calcite and opaline silica in wide adjacent bands within a single vein.
- The inability of this hypothesis to account for the development of vertical veins in sand-ramps.

- The commonly observed uniform and symmetric encrustation of cobbles by calcite downslope from faults.
- The lack of calcretes and veins in the exposed cone at Lathrop Wells.
- The common occurrence of vein breccias with floating textures.
- The lack of cementation of the ash within fissures at Trench 14.
- The orientation of the calcite-opal veins and "floating" tuff inclusions in Trench 14.
- The localized down-slope relationship of observed thick calcrete beds to faults and the localization of veins and calcretes at faults.

3.) Even if the rain-water/pedogenic mechanism is assumed to be 100 percent efficient, it is still much too slow a process to produce nearly pure calcite-opal banded vein deposits in competition with infilling by local country rock debris driven by wind and rain erosional processes.

4.) Finally, it is clear that observations of hydrothermal alteration along with vein calcites at a fault are difficult to explain using a pedogenic model.

In the light of these various problems and shortcomings, we have reached the conclusion that the rain-water/pedogenic hypothesis cannot be regarded as a realistic source mechanism for the calcite-opal veins, or most calcrete deposits, of the type observed.

V. Evaluation of Geochemical Evidence and the Isotopic Composition of Calcite-Opal Veins and Ground Waters

The CHT model proposed by Szymanski has some rather complex implications for the water circulation to be expected in a system that is controlled by these non-linear dynamical interactions. In particular, since the system would evolve through a series of dynamical states, as indicated in Figure 2, it can be expected that any water flow patterns would evolve and change with time as well. Furthermore, if a whole geologic region is tectonically active, as is most of the Basin and Range Province and in particular the area in the vicinity of the Nevada Test Site, then it might be expected that different parts of a large region would be in different stages of any evolutionary cycle that was occurring, simply because of heterogeneity in physical properties and tectonic conditions over a large area. Thus, local "systems", corresponding to relatively small geologic units such as Yucca Mountain, could be expected to be in different stages of deformation and their hydrological states would also reflect this situation. Consequently, the different geologic units would be expected to be in different stress and deformational states, to exhibit different thermal and fluid pressure states and, in the context of a CHT model, to be evolving with different time constants and strengths of interaction.

In terms of water flows that would be exhibited at a given time, some of the systems could be in a state dominated by thermal convection from large depth or by seismic pumping, while some would be dominated by simple gravity flow or a combination of gravity flow and localized (relatively shallow) convection. Since water flows will also involve degassing and deposition of minerals and will impart isotopic signatures to the deposits that are characteristic of the water involved, it would be expected that the ancient deposits of minerals within the geologic units would typically reflect a past hydraulic flow state when deposition was particularly efficient and wide-spread; such as would be the case during an episode of hydrothermal convection. Consequently, the current state of a hydrologic system and its flow characteristics would not ordinarily be expected to match the state which was responsible for most past mineral deposition; nor would the current character of the water at depth need to be like that which deposited the minerals. It also follows, therefore, that the isotopic characteristics of the minerals need not be similar to the water in the depth vicinity of the deposit, since the water actually involved in the deposition could have been a mixture of very deep water transported upward to the near surface and the local water. In a CHT dominated system this would, in fact, be the expectation.

In a series of responses to a publication on the isotopic character of the carbonate veins in Trench 14 by Quade and Cerling [9], Szymanski produced a series of letters and reports [5] in which he developed, in some detail, his view of what relationship vein mineral isotopes should have to the subsurface water at a site such as Yucca Mountain. To do so he used the idea that the area around Yucca Mountain, covering a large part of the Nevada Test site and its immediate surroundings, could be subdivided into spatial units corresponding to distinct hydrologic systems with special and identifiable characteristics. The basis of such a spatial partitioning was simply that if the whole region was controlled by tectonic interactions, as in a CHT model, some areas would be in a state largely dominated by up-welling of water from considerable depth while others, in a more stable state of the CHT cycle, would exhibit gravity dominated flow involving recharge and largely downward and lateral movement of shallow water. These two general types of hydrological systems were characterized as "sources" and "sinks" and because of the different flow characteristics could, in Szymanski's view, be identified from field evidence involving differences in thermal and pressure states and in water chemistry.

If such a subdivision into these two classes of systems exists, then the isotopic characteristics of the water in each group should differ, since the source and paths for the water in the two cases would be different. In particular, the isotopic characteristics of water samples from source areas involving up-welling from depth should differ from those in sink areas and, further, the isotopic abundances in the water from source areas should lie in the same range as those for vein calcites if these veins are indeed due to up-welling water controlled by a CHT mechanism.

Thus Szymanski, in effect, devised a direct test of his model based on observable isotopes from water samples at sites that are currently up-welling source areas. In the context of his model, conditions of up-welling would be expected to have produced the calcites at Trench 14 and elsewhere at Yucca Mountain in the past, but such conditions are no longer existent at the sites since the system has evolved to a current state that is closer to a "sink". Therefore the Yucca Mountain vein calcites (and many calcrete deposits) should not compare isotopically to the current shallow water at the site, but should be comparable to the water samples at other sites that are currently sources of up-welling; that is to a mix of deep and shallow water as produced in a up-welling state. To evaluate the relevance of the Szymanski CHT Model to the hydrology at Yucca Mountain it is therefore important to check whether the isotopic properties of the vein calcites can, in fact, be adequately fit in this way.

Hydrolic Source and Sink Areas: Comparisons of Ground Water Isotopes from "Source Zones" to Calcite Vein Isotopes

The source and sink concept used by Szymanski [5] is illustrate by the schematic in Figure 26. Here the convective cells illustrate zones of up-welling and down-going fluid motion. The regions between cells define a "source zone", where water is generally moving upward, or a "sink", where the water moves down. Here the sense of cell circulation alternates between cells, as is typically the case with convective systems. Since there is a flux of water downward from

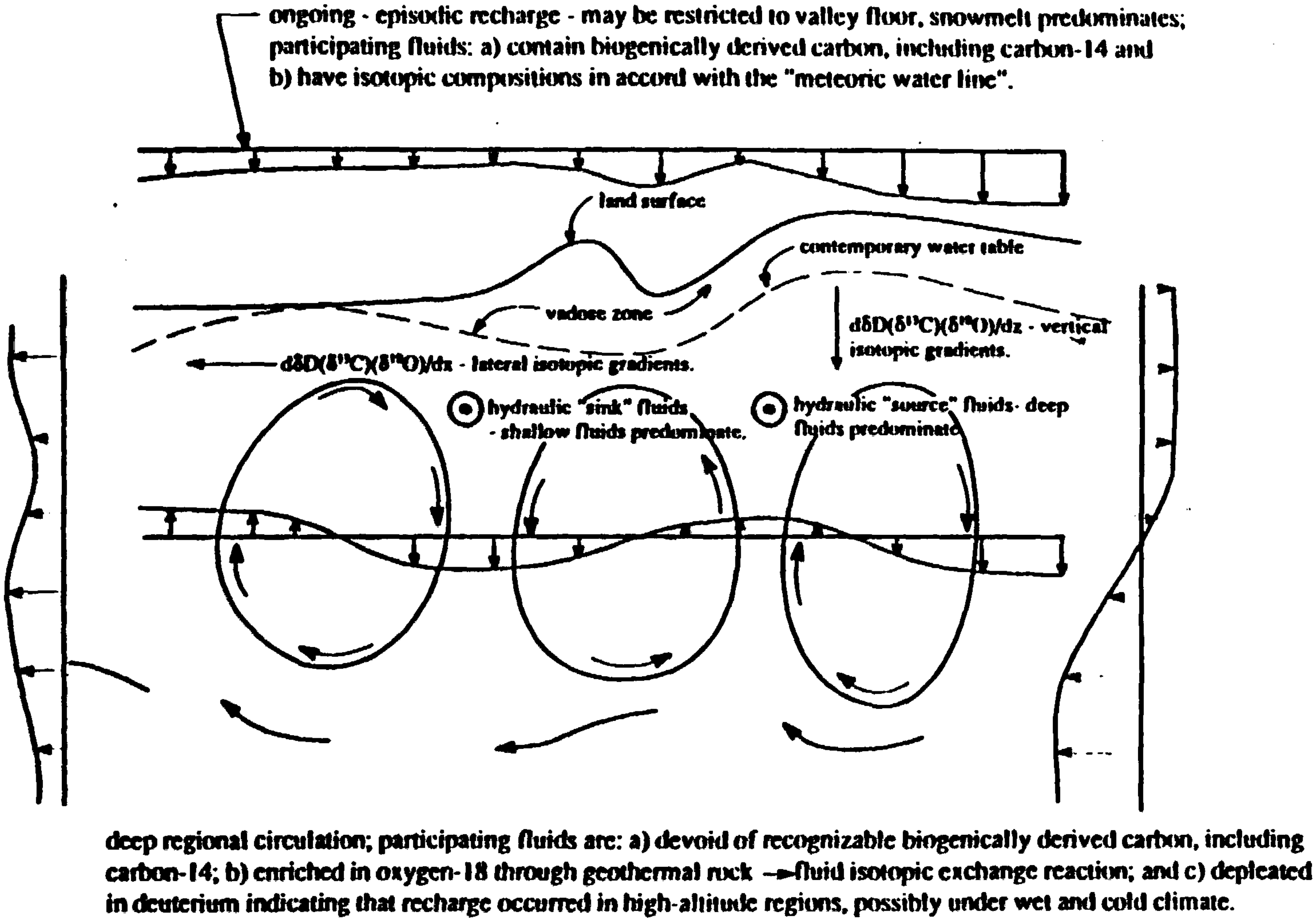


Fig. 26. - Schematic representing Szymanski's concept of the hydrological origins of "sources" and "sinks" in the water circulation in the Nevada Test Site hydrosphere. Due to the cyclic variations of the tectonically influenced hydrological environment, these circulation patterns would expected to shift spatially in time, with some source areas becoming sinks and vice-versa. The isotopic hydrochemistry would be strongly influenced by the deep circulation patterns indicated, with "source zones" being dominated by deep circulating fluids and "sinks" by the shallow fluids and meteoric recharge. Consequently, lateral and vertical isotopic gradients would be produced by spatially variable intermixing of deep and shallow fluids [5].

meteoric input and lateral fluxes into and out-of the region shown, any real patterns of flow would be distorted from those depicted because of these fluxes, as well as because of the spatial variability of porosity and permeability that would be expected in the actual earth medium. Therefore the patterns of flow could be more complicated than those suggested in the figure.

In trying to identify source and sink zones in the area surrounding Yucca Mountain, Szymanski used criteria involving observed thermal gradients, hydraulic gradients and water chemistry that he expected to be sensitive to, and indicative of, the sense of vertical flow. In particular, for source zones the criteria used was: An upward vertical hydraulic gradient; a high downward increasing temperature gradient; and high concentrations of chlorine, sulfate, sodium and potassium ions in solution. For sink zones the criteria are essentially that these variables would have considerably lower values, with the hydraulic gradient being downward instead of upward and the temperature gradient being significantly lower.

The problem in this approach is how to classify intermediate cases which would correspond, in the context of an evolving system, to something between the most extreme states; that is between a vigorous up-welling state and a true sink. In reality, assuming the model applies in the first place, one should expect a range of behavior between these extremes (*eg.* weak up-welling). Assigning zones as belonging to one (extreme) class or the other might therefore be somewhat arbitrary. This, of course, would be further complicated by a lack of complete, reliable data relating to the variables used in the partitioning process.

Nevertheless, if the approach is pursued, doing the best that can be down with the available data, a partitioning could be achieved that may be further tested. In particular, the indicators used by Szymanski can be used as a "first cut" along with other criteria, such as the presence of springs, to partition a region into "source" and "sink" zones. The other properties of the subsurface water from the zones, in particular their isotopic properties, can then be examined and compared. If the isotopic ratios that can be measured from subsurface waters in the various zones produce two separate, well defined distributions, then it would be appropriate to conclude that two different generic classes of water were present and that (most of) the zones in which these water types existed had been properly identified. If the isotopic properties of the waters from "source zones" and "sink zones' did not clearly separate, or overlapped strongly, then one might try other subdivisions in an effort to obtain a better resolution. Iterations of this sort should make it evident whether such distinct water types can be identified from the existing data or not - and probably whether they exist or not.

Figure 27 shows the distribution of source and sink zones identified by Szymanski on the basis of the criteria listed earlier. Here the Yucca Mountain area is labeled a "dilated region" while in his discussion he calls it a "hybrid source-sink", which refers to the combination of downward moving, "sink-like" flows in most of the upper subsurface penetrated by boreholes and upward, "source-like", convection in narrow zones along significant local faults, i.e., the Solitorio and Paintbrush Canyon Faults (see Figure 7). Thus, he views the Yucca Mountain area as being somewhere between a pure "sink" or pure "source" zone. This would likely be the case for other areas as well, and one would therefore expect some scatter in observations, producing, for example, a wider range in isotopic ratio data distributions from water samples within such zones than for the pure "source" or "sink" systems. Figure 28 shows a plot of the relative frequency of occurrence of measurements of the calcite saturation index when frequency plots for "source" and "sink" areas are computed independently using the zones identified in Figure 27 to separate the data. As would be expected, "source" zones, which are considered to involve up-welling water, show higher values of the saturation indices. The overlap in the two populations may, in part at least, be due to the presence of hybrid systems. Nevertheless, the data indicates two

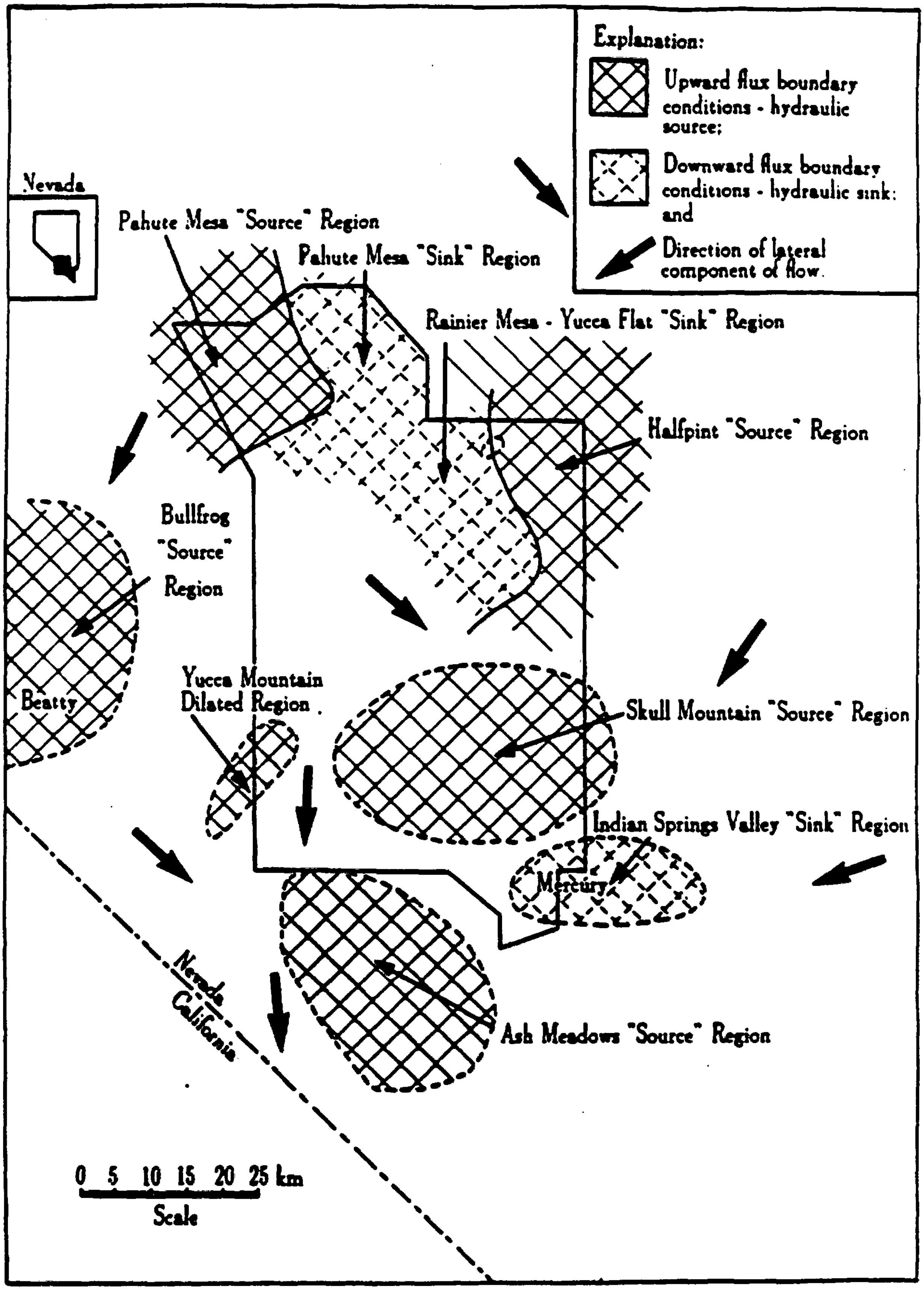


Fig. 27. - Distribution of hydraulic "source" and "sink" areas for the Nevada Test Site hydrosphere as inferred by Szymanski on the basis of temperature gradients, water chemistry and hydraulic gradients [5]. The present Yucca Mountain site, denoted as a "Dilated Region", is considered a source-sink hybred, with some convection only at large depth. It has, however, a past history as a pure source region, evolving as the tectonic stress and deformational state has changed it from a "source" to "sink" area.

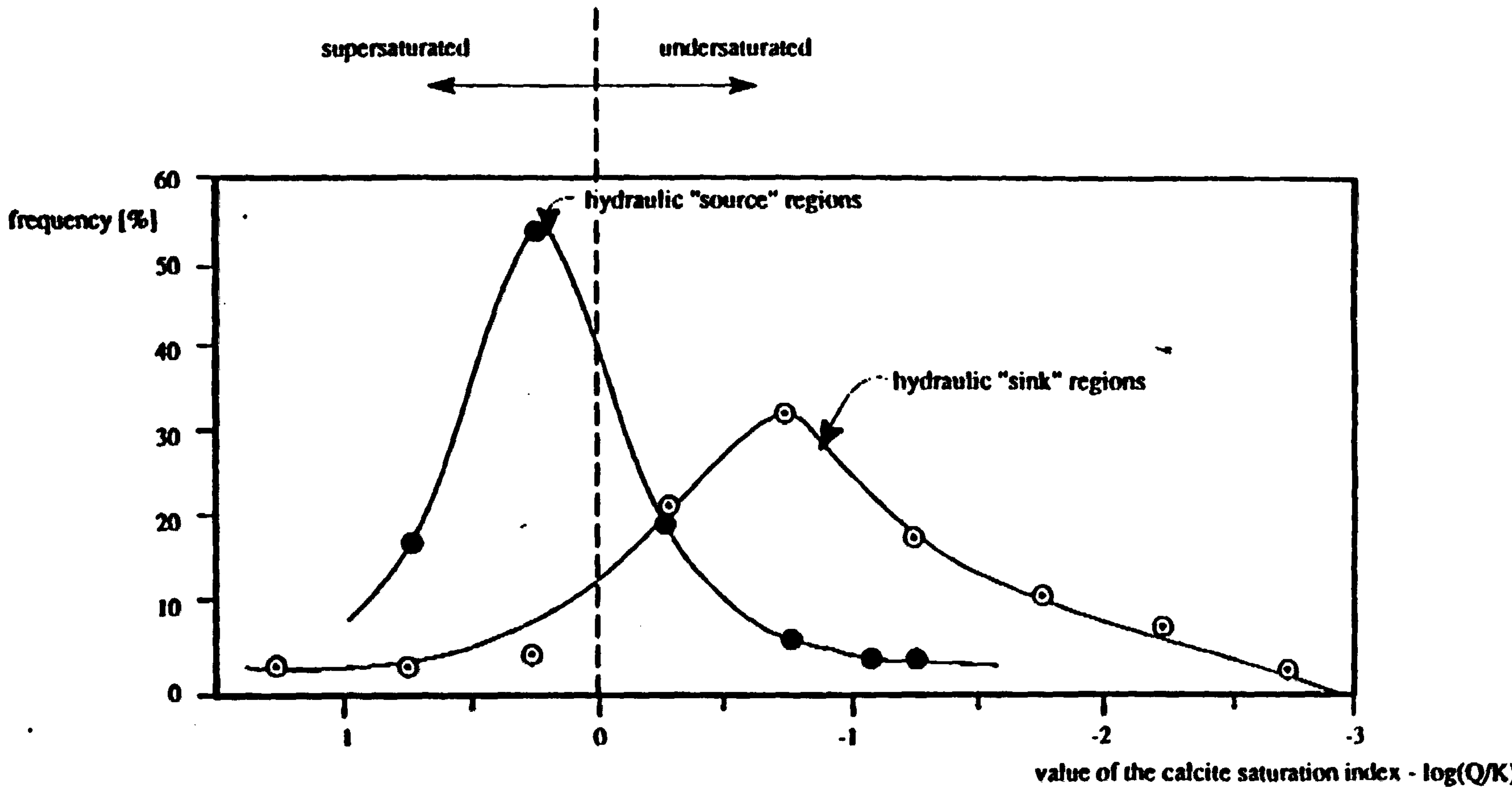


Fig. 28. - Relative frequency of observed calcite saturation index values for water samples at the hydraulic "sink" and "source" regions [5]. The data, separated and plotted for the two cases, produce two overlapping distributions with means that are reasonably well separated. A source region typically has a higher index value, as would be expected for a zone in which upwelling from depth occurs.

reasonably well separated distributions so that, with respect to this parameter at least, there does appear to be a significant difference in the water from the two types of zones.

Similar plots for isotopic oxygen and carbon in the waters for these two types of hydraulic regions are shown in Figures 29-31. In each case, when separately plotted, the "source" and "sink" zones waters result in distinct distributions of observations with significantly different means. We have added a frequency plot for the combined data from all areas taken together (shown as a dashed curve), superposed on the "source"-"sink" frequency curves provided by Szymanski. This plot allows us to assess whether the complete data set itself indicates a bi-modal distribution for the individual isotopes without imposition of any partitioning procedure. While this presentation of the data shows less dramatic indications of two partly overlapping distributions, it is evident that, taken together, the data indicate bi-modal behavior.

Some of the data, such as for Oxygen in Figure 29, shows rather weak indications of bi-model behavior, while the bi-modal distribution of the carbon isotopes is more evident. As shown by Szymanski's sample numbers on his "source" and "sink" frequency plots, considerably more of the sampling was done in source areas than sink areas, so that this sort of sampling bias tends to mute the evidence for bi-modularity in the composite distribution functions. This muting is, of course, removed by the partitioning used by Szymanski, as is evident from his separate distribution function plots. In any case, it is important that bi-modularity in the undifferentiated data can be detected, since this distribution is obviously not affected by the choices made by Szymanski in his partitioning and therefore provides an independent check of his hypothesis. Thus, the unpartitioned ("raw") data alone provide support for the concept of "sources" and "sinks" within an area involving basically different types of ground waters.

Figure 31 shows, in addition, the range of the $\delta^{13}C$ ratio for the calcite-silica deposits at

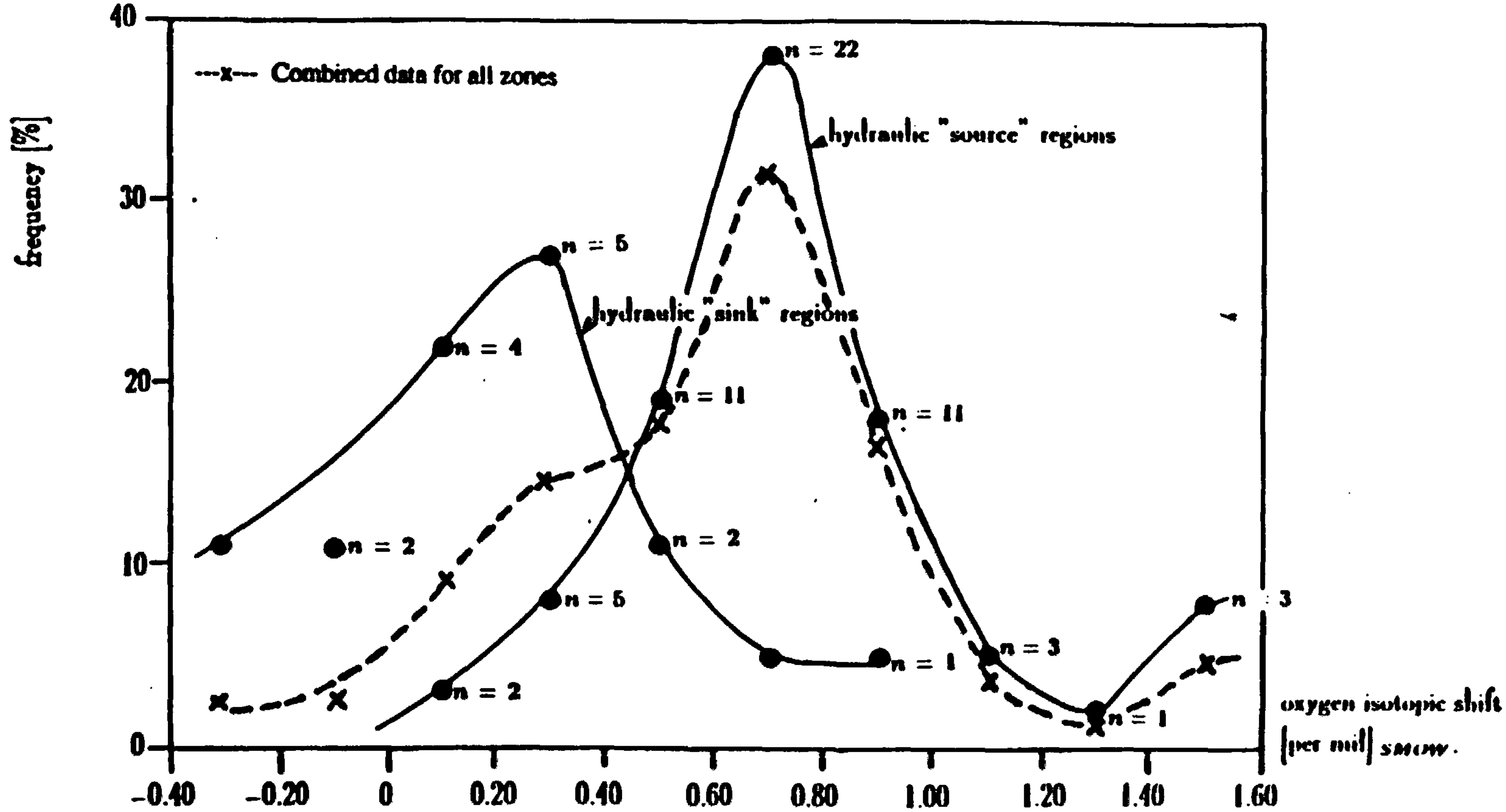


Fig. 29. - Comparison of the oxygen isotopic shift magnitudes from fluids pumped from exploratory wells in "source" and "sink" zones in the Nevada Test Site area [5]. The number indicated near the plotted points denotes the number of samples obtained within ±0.1 units of shift from the value at the point. The values are from bulk samples pumped from rather large intervals within exploratory wells and so are averages.

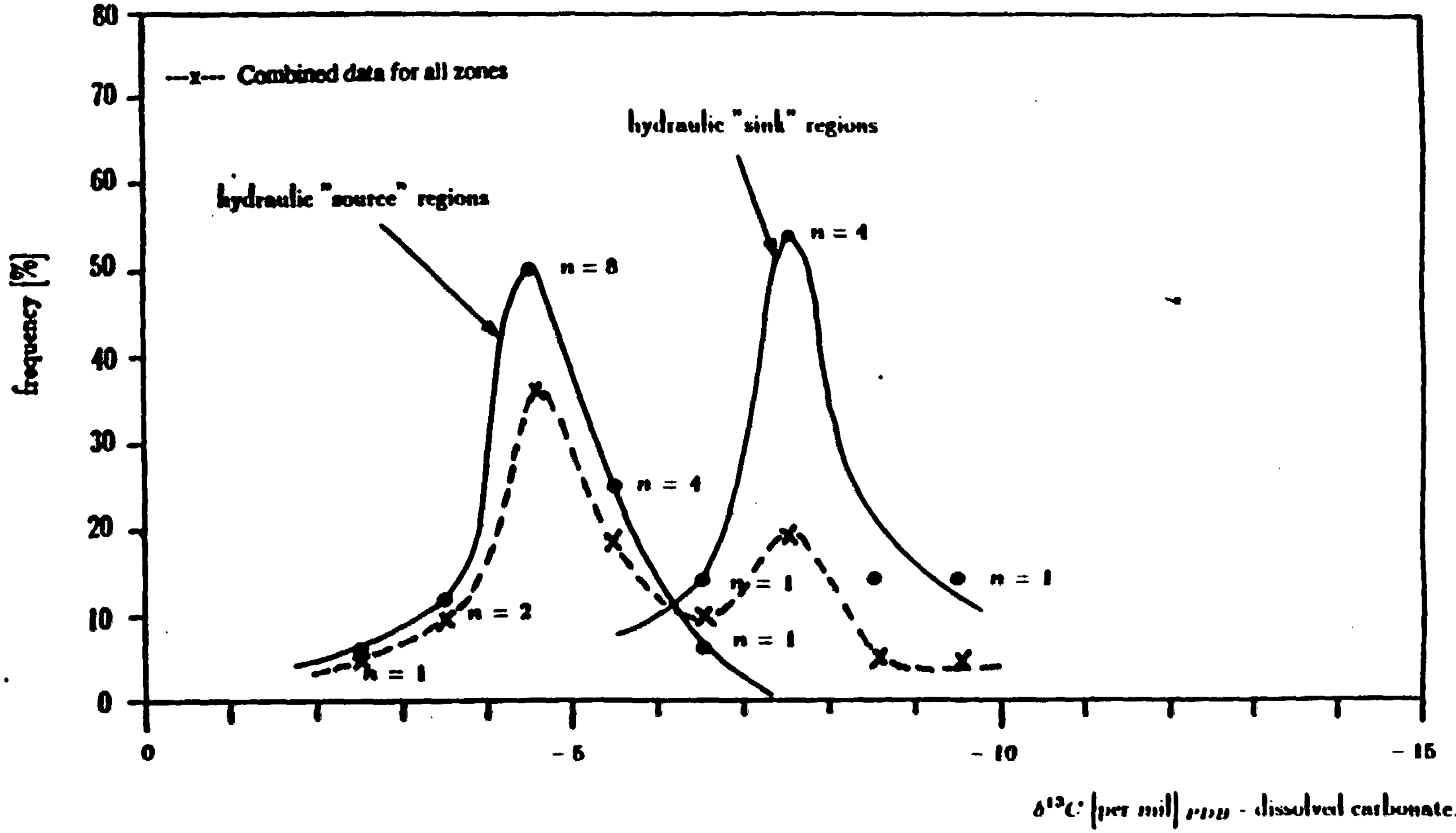


Fig. 30. - Isotopic character ($\delta^{13}C$ ratio) of dissolved carbon in water samples from the *paleozoic carbonates* at hydraulic "source" and sink" regions in the Nevada Test Site area [5].

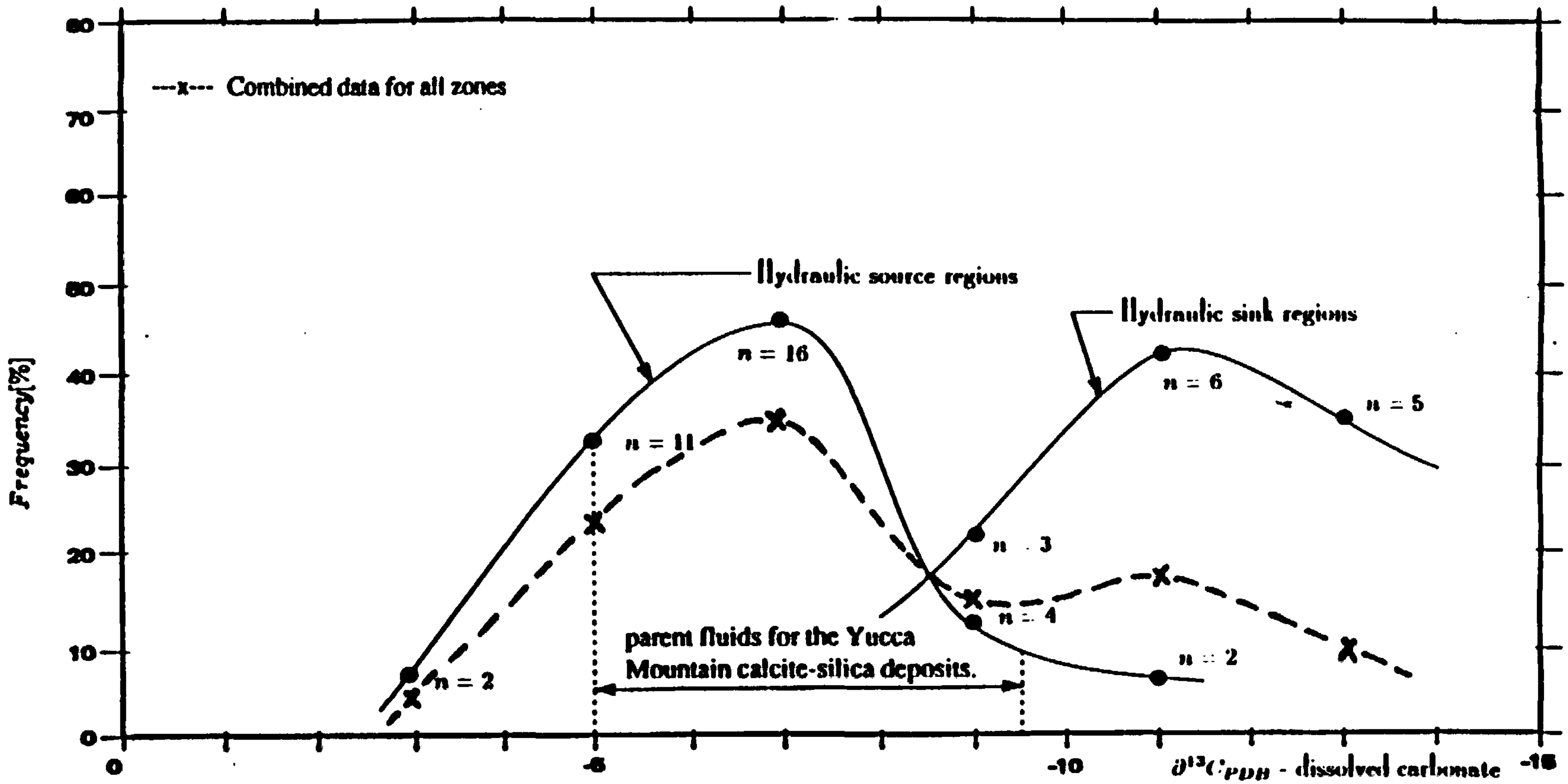


Fig. 31. - Isotopic character ($\delta^{13}C$ ratio) of dissolved carbon in water samples from the *alluvium-tuff zone* at hydraulic "source" and "sink" regions in the Nevada Test Site area. Also shown is the $\delta^{13}C$ range observed for the calcite-silica deposites at Yucca Mountain [5].

Yucca Mountain. Szymanski compares this with the relatively shallow water in the alluvium-tuff zone beneath "source" regions in the NTS area around Yucca Mountain. (Note that for such a depth range, the Yucca Mountain hydraulic system corresponds to a "sink"). For "source zones" the water at this depth should be of the type (mixed deep and shallow waters) producing near surface mineral deposits and so should be comparable to the calcite-opal deposits at Yucca Mountain. As indicated in the figure, this agreement is as required.

The unstable isotopes of Uranium and Strontium are also present in the water and vein calcite at the surface and at depth in the area and should produce similar relationships under this hypothesis. Indeed the postulated trends are found in the data, however, there are some complications in the isotopes of Uranium that are of interest, both in the present context and for later considerations.

In this regard Figure 32a,b shows plots of $^{234}U/^{238}U$ versus $^{230}Th/^{234}U$ with data from the NTS area, in Figure 32a, and with data from only Trench 14 and the nearby Busted Butte area in Figure 32b. The Uranium activity ratios for water sites at and near NTS are also shown in Figure 32b. These figures also show theoretically predicted loci of activity ratios, parameterized by age, for an isolated mineral sample in which only radioactive decay of unstable isotopes occur, without loss or exchange of isotopes with water or other mobile constituents that might be present.

The variable age data shown in Figure 32a is seen to have values of $^{234}U/^{238}U$ ratios that are usually below 1.75, with most in the range from 1.5 to 1.0. The similar data in Figure 32b all show $^{234}U/^{238}U$ ratios at or below 1.5. However, many data points in Figure 31a have $^{230}Th/^{234}U$ ratios between 1 and 1.3, while having low $^{234}U/^{238}U$ ratio values. As can be quickly deduced form the theoretical curves, most of these data points lie completely outside the

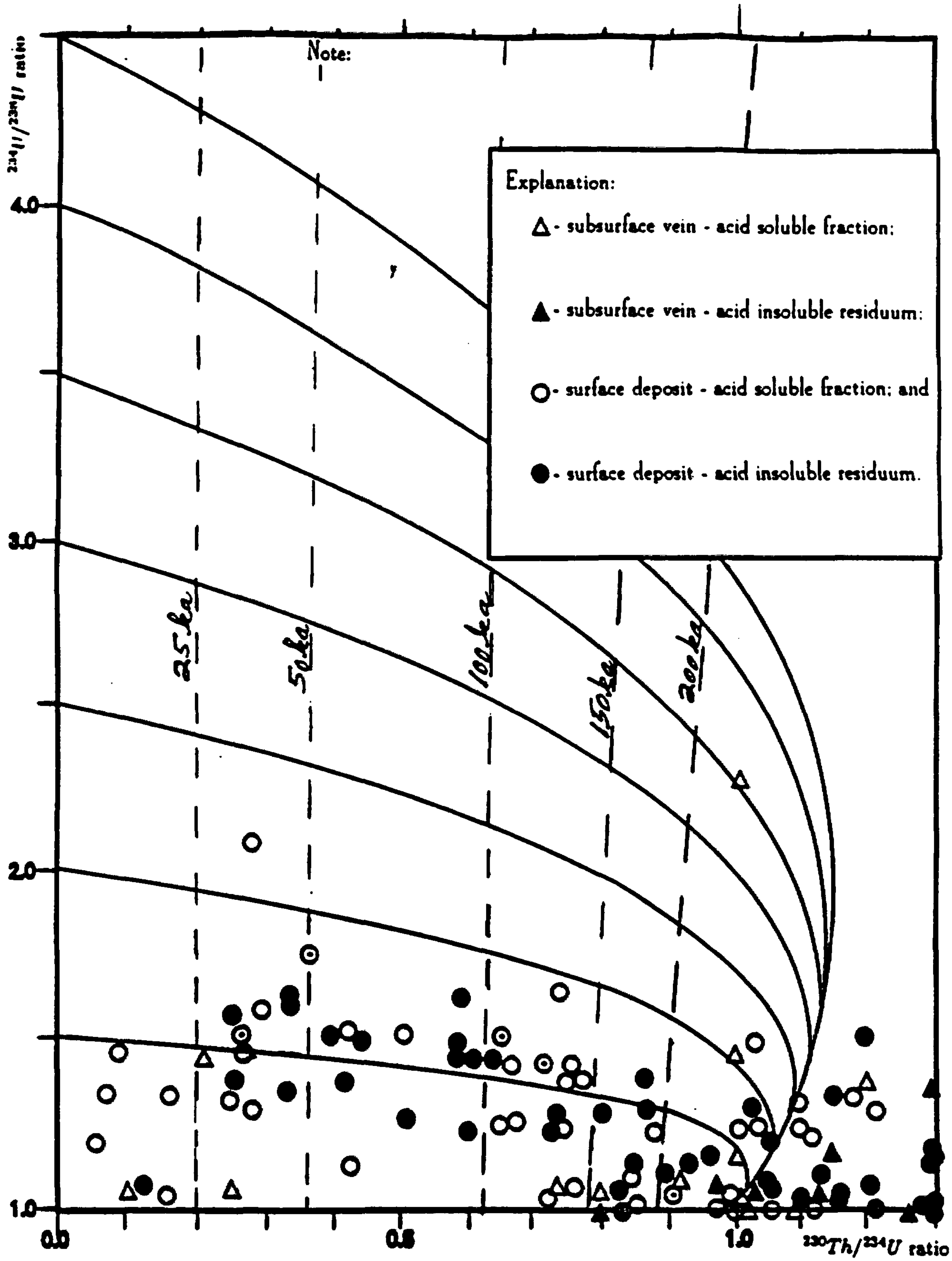


Fig.32a.- Observed $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios for Nevada Test Site Calcite-silica deposites [5].

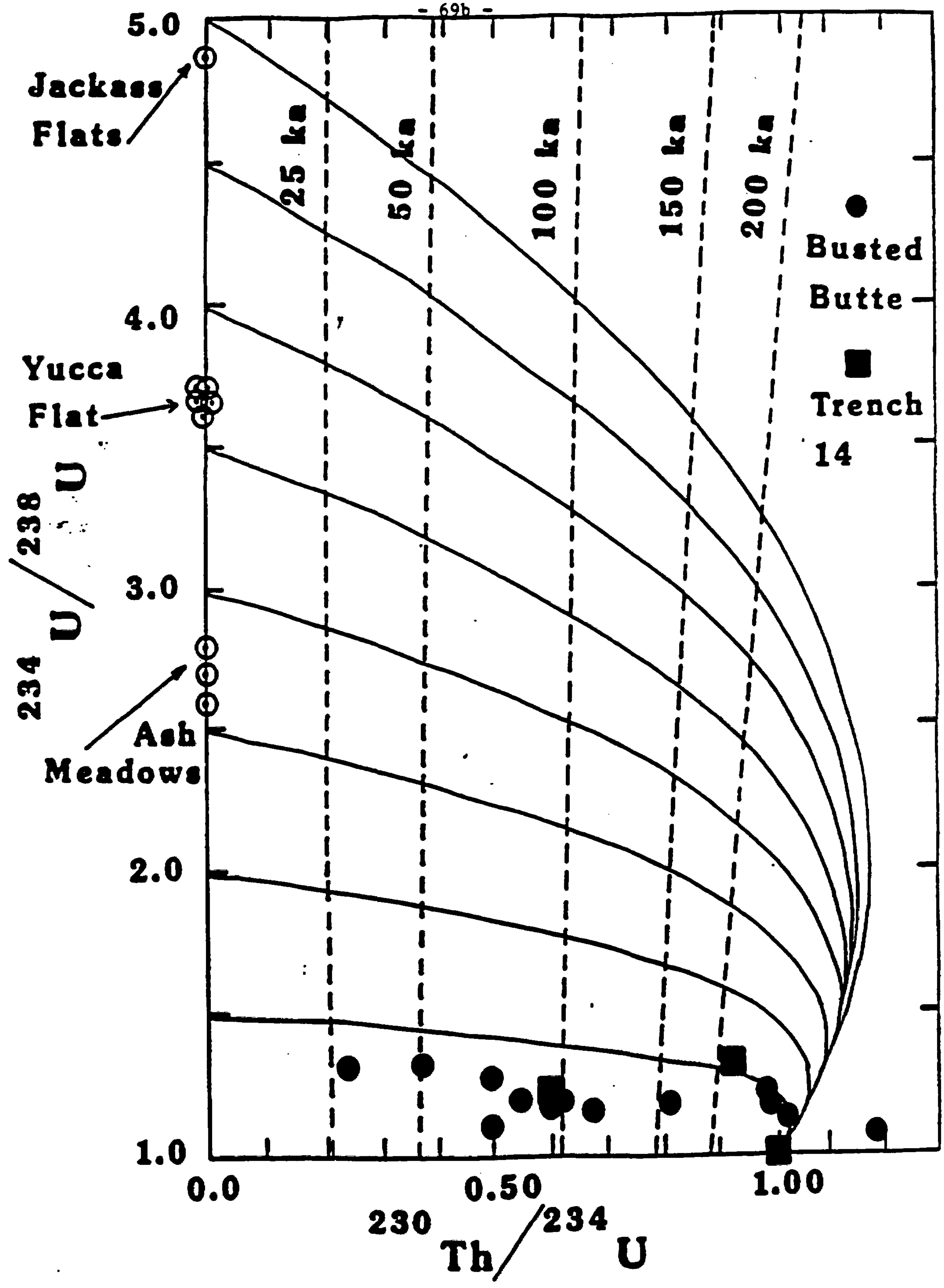


Fig. 32b. - Uranium and Thorium activity ratios for calcite veins and water with data as presented by Stuckless [36].

predicted value range of isotopic ratios for isolated samples of any age whatsoever. The same observation applies to the single point, on the lower right side shown in Figure 31b, for the sparser data set for Trench 14 and Busted Butte. Since the measurement uncertainties are relatively small (on the scale of the figures, the error bars are smaller than the size of the points shown), then it can only be concluded that these data points indicate that open system processes have resulted in large variations in the measured ratios from those for an idealized closed system. Further, all the data shown would be likely to have been affected by open system processes, not just those with the very high $^{230}Th/^{234}U$ ratios.

In our view, the mechanism most likely to be responsible for the very high $^{230}Th/^{234}U$ values in vein minerals exposed to water in fractures, and as well to result in lower values of $^{234}U/^{238}U$ in these minerals, involves the decay of the parent isotope (^{238}U) from which ^{234}U and energetic alpha particles are produced. In conserving momentum and energy during the decay process the ^{234}U nucleus acquire momentum and moves through the crystalline lattice, this usually being described simply as "alpha recoil". If the medium is macro- and micro-fractured with water in the fractures, then some of the ^{234}U atoms at fracture surfaces will be ejected directly into the fracture water while others will enter solution from damaged zones in the lattice. Thus ^{234}U is lost from the solid and added to the water. This mechanism will therefore produce disequilibrium between ^{234}U and its parent isotope ^{238}U in both the water and the crystalline material, in that the $^{234}U/^{238}U$ ratio in the water will be increased over that normally expected (the water solubility of both Uranium isotopes are essentially identical) while the $^{234}U/^{238}U$ ratio in the solid will be decreased from that expected in an isolated crystalline sample.†

†The disequilibrium in the water due to this "alpha recoil" mechanism was noted by Stuckless et al. [38], but they do not mention that it would also necessarily produce disequilibrium in the $^{234}U/^{238}U$ ratio in the vein material in contact with such water.

The consequences, in terms of the data in Figures 32a and b, are that the vein mineral data values will have lowered $^{234}U/^{238}U$ values and increased $^{230}Th/^{234}U$ values, over those in a closed isolated system, due to the alpha recoil mechanism ejection of ^{234}U atoms from in the crystalline material and absorption of the recoil atom by fracture water. Therefore, to interpret the data in Figure 31a using the normal decay curves for an idealized closed system, it would be necessary to apply a correction in the direction of decreasing the $^{230}Th/^{234}U$ values and increasing the $^{234}U/^{238}U$ values for mineral samples to account for open system influences. A similar correction would, of course, apply to the Yucca Mountain-Busted Butte vein data in Figure 32b. Thus, a correction is necessary for the vein material if we wish to use the decay curves to obtain estimates of initial ratios of $^{234}U/^{238}U$ at the time of water deposition ($^{230}Th/^{234}U = 0$ at this time, since ^{230}Th is essentially insoluble in water) and if we wish to compare this initial ratio to that of available depositional waters. The water, however it acquires its Uranium isotope character, will set the initial Uranium ratio of the precipitated vein material. Therefore comparisons are made to water samples as observed, without adjustment.

It is difficult (at least at this time) to accurately estimate the size of the correction required; although from the data distribution at high values for the $^{230}Th/^{234}U$ ratio in Figure 32a we conclude that the correction is at least about a .3 unit decrease in the $^{230}Th/^{234}U$ ratio for the older vein minerals. (This correction would bring the data within the envelope of the closed system decay curves shown.) The $^{234}U/^{238}U$ correction would also to be of this order, but involve an increase in value. However, different ages of the vein minerals are represented in the data and, because the effect must decrease with decreasing age, the size of the correction will decrease for the younger mineral samples.

Compensating for open system trends in this manner implies that age estimates obtained from uncorrected data may be too large; that is the corrections have the effect of producing younger estimates for the age of formation. Although not in itself conclusive, it is worth noting that this trend for over-estimating ages using closed system theory is born out by data where independent age estimates were obtained using decay rates for ^{14}C [45].

Consequently, if we apply corrections of roughly this size (ratio corrections of .3 units) to the data of older apparent age and, say, linearly decreasing corrections to the younger samples in order to allow estimates of initial values of the Uranium ratio (at which point $^{230}Th/^{234}U = 0$) using the decay curves, we find initial $^{234}U/^{238}U$ values for NTS area vein minerals that lie in the range from about 1.25 to 3.5, with most in the range from 2.0 to 2.5. (These may be "conservative" values, in that the corrections could be somewhat larger and if so would result in higher values for the initial $^{234}U/^{238}U$ ratios.) For the Trench 14 and Busted Butte data in Figure 32b, the range would be more clustered, from around 1.5 to 2.25. However, we are not sure that the data shown represents all the most recent data for these latter sites. The values for water samples at Ash meadows and other sites, shown in Figure 32b are still, however, quite different than the values for the veins.

Nevertheless, these considerations will have an important impact on the comparisons of Uranium isotopic ratios of the water at Yucca Mountain relative to initial values for the vein minerals at Trench 14 and elsewhere. For example, the Figure 4 in the paper by Stuckless *et al.* [38] shows superimposed histograms of the $^{234}U/^{238}U$ ratios for Paleozoic water at Yucca Mountain along with the (uncorrected) vein mineral ratios. If the correction in the amount suggested earlier is used, taking account of the age and decay rates of Uranium isotopes in the vein minerals, then the histograms for the Paleozoic water and the (corrected) vein minerals at Yucca Mountain will have much stronger overlaps. Thus, given the conservative nature of the correc-

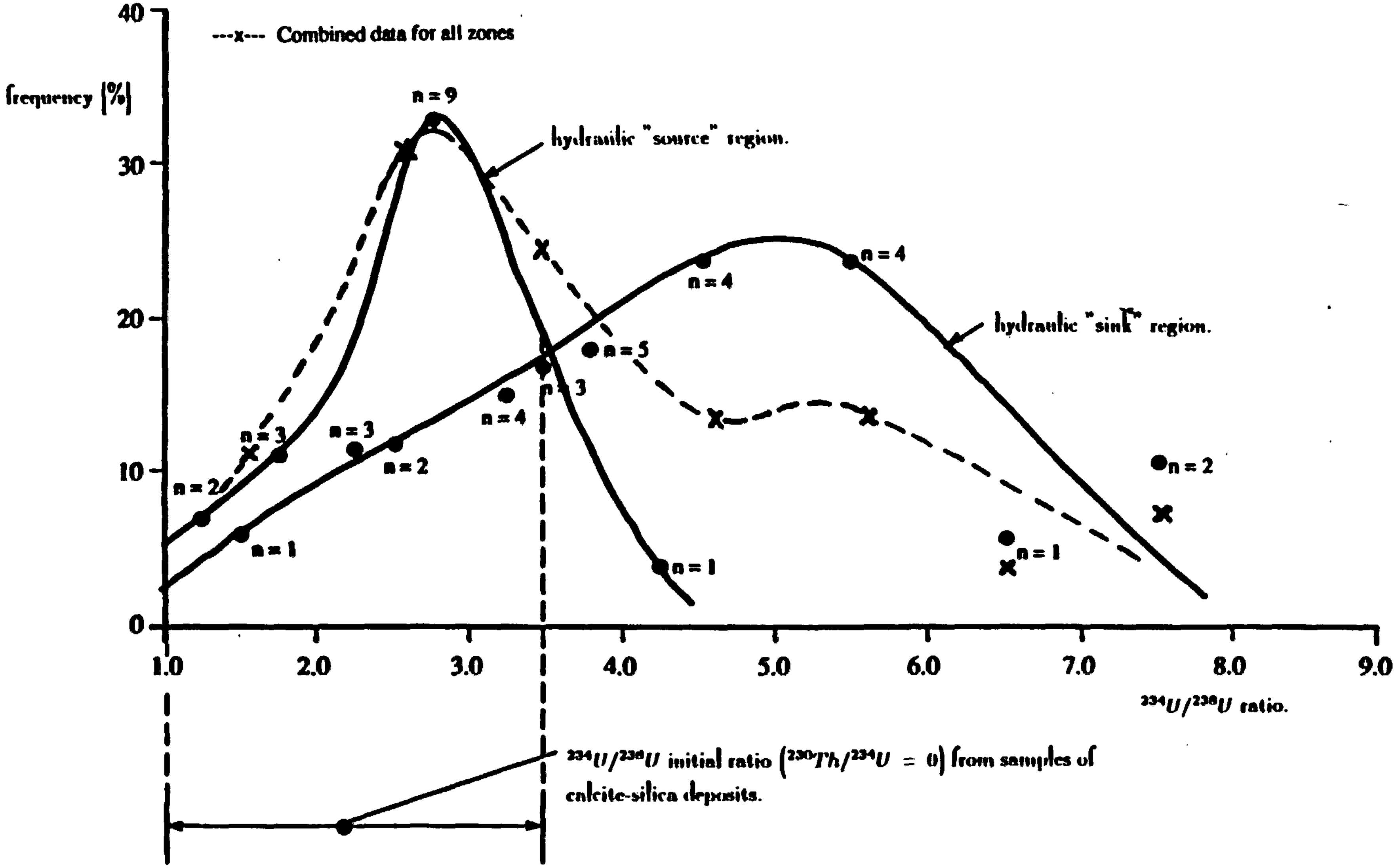


Fig. 33. - Distribution of observed $^{234}U/^{238}U$ activity ratios from water samples at hydraulic "source" and "sink" regions in the Nevada Test Site area. The inferred initial ratio (at $^{230}Th/^{234}U = 0$) for calcite-silica samples at Yucca Mountain are also shown [5].

tion and the wider sample distribution to higher $^{234}U/^{238}U$ ratios implied by the data in Figure 32a, we conclude that there is reasonably good agreement between the Uranium isotope values for the Paleozoic depth water and those appropriate to the initial values for the vein minerals at Yucca Mountain; in particular those for veins at Trench 14.

When the Uranium isotopic ratio data is partitioned on the basis of "sources" and "sinks" by Szymanski, the resulting distributions have the form shown in Figure 33. The range for the $^{234}U/^{238}U$ initial ratio is shown for samples from calcite-silica veins, at the surface and at depth, at Yucca Mountain. The initial ratio values cover the range inferred for the corrected data, as described earlier in relation to Figure 32a. The range of the water $^{234}U/^{238}U$ ratio for "source" regions in the NTS area is consistent with that for the vein minerals at Yucca Mountain and both distributions actually peak near the same value, near 2.5.

The distribution of Uranium isotropic ratios for the water from sink zones is very broad, probably reflecting the range of disequilibrium for ^{234}U relative to ^{238}U in water from relatively shallow zones where fracture porosity may be highly variable and the degree of disequilibrium in the water correspondingly variable from place to place. The distribution of values for all samples, taken together, is shown as the dashed curve. As for the Carbon and Oxygen isotopes, the composite distribution function indicates bi-modal behavior, which manifests itself even without partitioning of the data. Again, the match of the vein mineral Uranium isotope ratios to upwelling water at "source" regions is quite good.

An important isotopic characteristic of vein minerals in the area is the range of values observed for the Strontium isotopes. Figure 34 shows the range for Yucca Mountain $^{87}Sr/^{86}Sr$ ratios in calcretes and veins as compared to the distributions of the ratio in water from "source" and "sink" zones. The mineral range agrees with that for water from the "source" areas, again

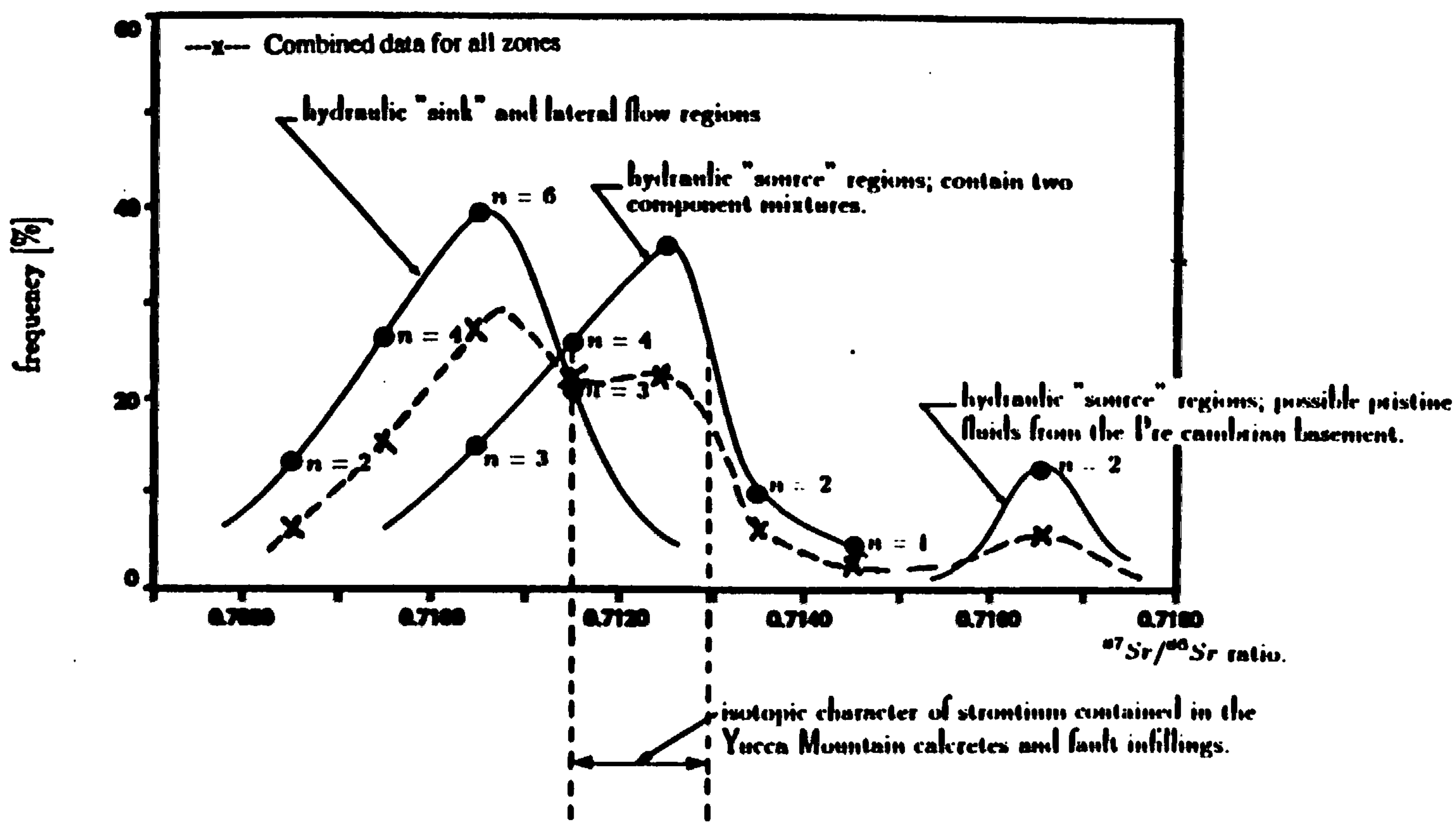


Fig. 34. - Distribution of observed $^{87}Sr/^{86}Sr$ ratios from water samples at "source" and "sink" sites within the Nevada Test Site area. Also shown are the observed strontium ratios for the calcretes and veins at Yucca Mountain [5].

implying a good fit to the water from deep up-welling sources. Szymanski has indicated what he believes is a manifestation, from two "source" water samples, of up-welling water from the Pre-Cambrian basement. These two isolated samples have high $^{87}Sr/^{86}Sr$ ratios near .7165. The curve representing the composite of all the data taken together, without partitioning, shows reasonably clear evidence of bi-modal structure, with a hint of an anomaly at the very high ratio values.

We regard Szymanski's demonstration of compatibility of the CHT model predictions of deep up-welling water as the source of the vein calcite-silica deposits and calcretes at Yucca Mountain to be quite convincing. The distributions of all the NTS isotopic data, involving isotopes of Carbon, Oxygen, Uranium and Strontium, all show indications of bi-modal structure. When all these data are partitioned on the basis of temperature and pressure gradient criteria, and then normalized to remove sampling bias, the data clearly show distinct distributions of isotopic character for the water, with that characterized as "source zone" water being, in all cases, compatible with the surface vein and calcrete data as well as the isotopic data from veins at depth.

Because the "source zone" characterization is based on high thermal gradients and upward pressure gradients in the water, it follows that these zones involve upward moving water flows from depth. However, it is not possible to ascertain from what depths the water is convecting, so that we cannot be absolutely sure that it is from a very deep zone, nor can we ascertain to what (quantitative) degree the observations represent mixing of deep, shallow and infiltrating water.

While we conclude that the isotopic data can be explained in terms of "up-welling water" from the "source" zones identified by Szymanski, we cannot conclude that this "fit", by itself, provides a definitive determination of the source of the calcium-silica veins and calcretes at Yucca Mountain, since to do so requires that we also demonstrate that water welled up in the past at Yucca Mountain in a manner similar to that now taking place at the various "source zones" identified by Szymanski. Thus, what has been demonstrated is that if water did well up in this manner then it would have deposited vein and calcretes with the isotopic characteristics seen in the field samples. In short, what has been demonstrated is compatibility with the CHT model, not a proof that it is requfred to explain the data.

Consequently, it is necessary to evaluate other possibilities in order to judge whether the mechanism proposed by Szymanski is required by this data. (This amounts to the attempt of a proof by elimination of all other possibilities.) However, it is quite possible that the isotopic data is ambiguous, in that more than one mechanism or process can adequately fit the observed data. That is, there may not be a unique "model" implied or required by the data. If not, then this should be made clear now, if possible.

Pedogenic, Descending Water, Correlations with the Calcium-Silica Vein and Calcrete Isotopic Data at Yucca Mountain

The "Pedogenic Model" deposition vein and surface parallel calcite-silica minerals represents the only other proposed explanation of the origin of these mineral deposits. In order to evaluate both the CHT model and the "pedogenic alternative", project scientists have focused on the isotopic data from veins and calcretes, principally those at Trench 14, in an effort to obtain an unambiguous determination of which of the models fits the observations. The recent articles by Quade and Cerling [9] and Struckless *et al.* [38] have been particularly assertive in this regard, having concluded that up-welling water cannot explain the isotopic data from the veins and that a pedogenic origin is required. However, we have described results from Szymanski's correlative study of the vein and calcrete isotopes relative to in subsurface water from areas deduced to be up-welling and find evidence for a strong correlation. This correlation then leads to the conclusion that the veins and calcretes at Yucca Mountain could have been formed by up-welling water from great depth.

In view of these contrasting conclusions, it is clear that one or the other (or both) must be in error. In this regard, it is not unusual for a conclusion to be based on unstated, and possibly unrecognized, assumptions. This often results in an overextended conclusion that is not warranted. This appears to be the case with the final conclusions stated by both Quade and Cerling and by Struckless *et al.*

We summarize our review of the Quade and Cerling arguments first, and focus on the basis for their conclusion rather than on the details of their analysis. In this regard, Quade and Cerling use calcite incrusted pebbles, cobbles and "soil calcretes" as their comparative reference, or standard, for a pedogenic deposit produced by rain water deposition. They then go on, after a series of arguments and corrections to the carbon and Oxygen isotopic data from these calcites, to compare the resulting isotopic data to that from Trench 14 vein calcites. However, they have *assumed* that the soil calcretes and encrustations are of pedogenic (rain water) origin, but they may not be.

In fact, as discussed in the previous section and illustrated in Figure 11, calcretes and calcites incrusted cobbles are seen at and near Yucca Mountain in relationships down-slope from fault zones where up-welling water flows may have occurred. Indeed, our judgement was that, for at least those deposits that were seen by us, the most likely water source for deposition of the calcite in the down-slope calcrete and cobble zones was from up-welling water along the fault zones. In addition, reworking of surface spring deposits or fault zone vein deposits by infiltrating rain water moving down and then laterally through alluvial materials and soils could produce secondary calcite deposits having a "mixed" isotopic signature, reflecting both primary and secondary dispositional origins.

If some or many of the calcite samples used in the Quade and Cerling study were due to either of these processes (up-welling or reworking), then the "soil calcites" used in the comparison would not have a valid, purely "pedogenic" origin as assumed and the comparison would, or could, indicate an up-welling water origin instead. Therefore, the comparison hinges on the assumption of a pedogenic, descending rain water, origin for the soil calcretes and encrustations in order that the conclusion reached be valid; which was that the carbon and Oxygen isotopes in the vein material require a pedogenic origin.

On the other hand, if the sampling of encrustations and soil calcretes was successful in isolating young, near surface pedogenic deposits of rain water origin, then the Trench 14 vein calcites would appear to have carbon and Oxygen isotopic characteristics compatible with those of pedogenic origin. This would be permissive evidence that a pedogenic process involving infiltrating rain water is allowed as the depositional mechanism on the basis of carbon and oxygen isotopic data, but is not evidence that only a pedogenic origin is possible. Indeed both a pedogenic process and up-welling may be possible and compatible with the carbon and oxygen isotope data. The only way to eliminate an up-welling source is by comparison of isotopic content from water sources of this type to the isotopic character of the vein minerals in question. However, as has been noted earlier the "source region" water samples identified by Szymanski also correlate with the isotopic data from the veins. Therefore, assuming the isotopic signatures also match those for infiltrating rain water, both mechanisms must be allowed as possibilities and the Carbon and Oxygen isotopic data do not appear to differentiate between them.

The study by Stuckless *et al.* compared additional isotopic data, in particular isotopes of Uranium and Strontium, from the veins at Trench 14 to both "standard pedogenic carbonates" and to the relatively shallow water beneath Yucca Mountain. With regard to the comparison of $^{87}Sr/^{86}Sr$ to the "pedogenic carbonate" ratios used by them, we again note that the pedogenic standard used was asserted to be of pedogenic origin but, as with the previous study, this need not be the case. What were assumed or concluded to be pedogenic deposits in the area could well have an up-welling water origin. Therefore the comparison of the vein carbonate ratios to such a standard, which does not produce a particularly strong correlation in any case, begs the question and a conclusion cannot be drawn on this basis.

The comparison of the Trench 14 vein isotopes to the isotopes in water from bore holes in the tuffs at Yucca mountain, on the other hand, are in essential agreement with the conclusion reached by Szymanski in his correlation study of "source" and "sink" region waters. That is, the relatively shallow water at Yucca Mountain represents a current sink zone and consists of downward moving meteoric water that does not (and should not) correlate with vein calcites and calcretes. Thus, what has been demonstrated is *not* that "all modes of origin that require bringing water from depth to form vertical vein deposits can be ruled out", as stated by the authors, but that shallow water, consisting primarily of downward moving meteoric water, is not the origin. The proposition that the vein calcite deposition was from deep up-welling water mixing with shallow water is not addressed by this study, since none of the water data was from the deep zone (greater than 1.5 to 2 km) that is considered to contribute to the deposition process, although it is worth noting that the water from the single borehole to penetrate the underlying limestone formation, i.e., UE25 P-1, came closest to matching the ratios for both Strontium and Uranium.

On the other hand, the correlation of the vein isotopes with the "source regions" where the water is probably a mixture of deep and shallow up-welling (convecting) water *does* constitute evidence that such a mix can produce water with isotropic properties matching the vein calcretes at Trench 14 and elsewhere at Yucca Mountain under similar convective conditions. Thus, if these conditions existed in the past, then both the veins at depth and at the surface would be expected to have the isotropic characteristics that are currently observed.

On the basis of this review, we have concluded that neither the pedogenic nor the up-welling water mechanisms can be ruled out as being responsible for the calcite-opal veins and calcretes at Trench 14, or other areas at Yucca Mountain, on the basis of isotopic comparisons, at least by us. However, in order to properly evaluate a pedogenic origin, the basis for assumptions of pedogenic standards should be stated and examined since these standards obviously play a critical part in the argument. In addition, a number of rather important details regarding corrections and interpretations of the pedogenic related isotropic data are in dispute, as is evident from comments and discussion by Szymanski [5] and by Cerling and Quade [42]. It is not clear to us, as non-specialists, how and in what direction all of these problems will be resolved. However, we note that the isotopic data involves open system interactions, such as the alpha-recoil effects discussed earlier. It appears to us that these effects have not been carefully addressed, or accounted for, in some of the studies. Likewise the possibility that rain-water reworking of earlier surface vein deposits, possibly of up-welling water origin, has not been considered.

We are therefore of the opinion that much has to be done before definitive conclusions can be reached using the isotropic data. However, if anything, the correlations obtained by Szymanski, as described earlier, may be the best way of investigating the isotopic relationships between existing water and vein isotope data. Much more data would certainly be appropriate, however, in order to firm-up the somewhat preliminary correlations obtained.

Finally we note that if the observation by Whelan and Stuckless [14], based on carbon isotope data from vein calcites at depth at Yucca Mountain, that the water table "may have varied from about 300 meters below to 500 meters above its present position" is unambiguously substantiated and reflects a recent history of such changes, then the case for up-welling water at Yucca Mountain would, in our view, be made. Even without this finding however, we conclude that the available isotopic data from the vein minerals both at the surface and at depth imply that up-welling water from considerable depth, when mixed by the flow process with the shallower water, is the probable source of these calcite-opal deposits.

Other Geochemical Data and Observations At Yucca Mountain

Table 1 indicates base metal concentrations at Yucca Mountain ([16], [18]), where the concentrations from silicified breccia in Trench 14 can be compared to the mean values obtained in the Yucca Mountain area around Trench 14. Higher concentrations of base metals, particularly from the section on the "north wall", than are found as background mean values, suggest that hydrothermal fluids may have been involved in the formation of these breccias.

Table 1 - Base Metals: Concentrations at Yucca Mountain

		Ag	As	Au	Cu	Hg	Mo	Pb	Sb	Tl.	Zn	Bi	Cd
Mean values - Yucca Mnt. [ppm]		0.026	3.07	0.001	6.88	<0.10	0.10	0.25	0.25	0.50	1.00	0.25	0.10
silicified "mosaic" breccia from Trench #14	north wall	0.034	7.93	0.004	7.15	0.122	0.507	7.75	<0.247	<0.494	23.0	0.504	<0.099
	north wall	0.423	110.0	0.005	27.9	0.700	65.3	154.0	24.6	<0.497	31.2	<0.249	2.12
	south wall	0.031	7.31	0.002	4.52	0.147	0.422	5.31	<0.245	<0.49	19.0	<0.245	<0.090

While it is generally agreed that much of the calcite at Trench 14 was deposited by modest to low temperature fluids near 20°C, it is probable that these silicified breccias were formed at an earlier stage with higher temperature fluids involved. The data suggest, in any case, that welling up of higher temperature fluids may have occurred during the early formation of the vein structure. However, there appear to be other mechanisms that could be responsible for such relatively mild metal concentrations, particularly in the early chemical history of the hot volcanic tuffs in the area, so that an unambiguous interpretation is not presently available. However, a more systematic and in-depth study is certainly appropriate [20].

Additional geochemical data regarding metal content in pore water at depth at Yucca mountain [21] is also suggestive. In particular, similarly high concentrations of base and noble metals were obtained from water samples from isolated pores in the tuffs at depth. The high metal concentrations in such pores suggest that hydrothermal water, up-welling during past periods of convection at the site, could have been trapped by the sealing produced by accompanying calcite precipitation and so now represent samples of this ancient water. As with the calcite veins themselves however, there is uncertainty as to the age of these inclusions. In particular, they could be old relative to the time scale of importance here. Further, there are other possibilities for the interpretation of these metal concentrations in the pore waters which require careful consideration before a final conclusion is warranted.

Nevertheless, taken together, these observations and those of hypothermal alternation of the tuff surrounding calcite veins at depth (see Figure 22) strongly imply high temperature water intrusion into the entire depth section beneath Yucca Mountain, up to the surface. If this proves to be certain or highly probable, then the critical question would be: when did the most recent intrusion occur and how frequently have they occurred in the past.

VI. An Analysis of Conditions for Dilation of a Fractured and Faulted Medium: Dilation of the Upper Crust at Yucca Mountain

An important feature of the CHT model for Yucca Mountain is the gradual opening of fractures under extensional strain, with the region containing many open fractures (a dilated zone [22]) slowly expanding from the near surface to greater depths in the crust. This downward expanding zone of dilation has been described by Szymanski in terms of the movement of a surface, the "Z surface", that separates the shallow zone containing many open iradically spaced fractures, from the deeper crustal zone containing few open fractures.

While we expect that such a neat geometric division of the upper crust at Yucca Mountain into dilatant and non-dilatant zones as a function of depth and time may be an over-simplification in view of heterogeneous material properties and the strongly non-uniform distribution of pre-existing faults and fractures, we nevertheless feel that there is strong evidence for an open fracture system currently existing at Yucca Mountain and that it extends from the surface to well within the saturated zone. We wish to investigate how such a zone can be formed and whether it can be expected to have the spatial extent and time dependent growth consistent with the Szymanski model. More specifically, it might well be expected, in such a heavily faulted area as Yucca Mountain, that most of the extension would occur along the weak fault zones and not within the medium surrounding or between the faults. In this case the faults would tend to "absorb" the extensional deformation because they are so weak and opening along existing or newly created fractures in the bulk of the medium might be minimal. Our question is, therefore, whether such a faulted and fractured medium allows spatially extended dilatancy, characterized by a high volume density of open fractures, and if so under what conditions.

The importance of this question relates not only to one particular aspect of the Szymanski model, but also to the likelyhood of large volume water and gas flows in the upper crust following a major tectonic event. Clearly the magnitude and character of such flows would be dependent on the nature of the open fracture system within the medium. In particular, a dominance of connected and vertically oriented open fractures throughout the depth section of the mountain would permit maximum vertical flow effects from large depths. Such flows are expected by Szymanski to be pressure driven initially, due to rapid stress field changes associated with a tectonic event, and thermally driven in a later, longer lasting, flow that would be allowed by localized increases in the fracture porosity and permeability in existing crustal sections exhibiting high thermal gradients. Thus, since quantitative estimates of the nature and magnitude of pressure driven seismic pumping are dependent on valid estimates of both the natural porosity of the medium and, more importantly, on the fracture porosity and permeability, it is important that the conditions for dilatancy be established. Furthermore, thermally driven convection from depths of several kilometers in the upper crust could also be expected to be controlled, to a large extent, by existing fracture porosity and the orientation and distribution of the fractures. Thus, in terms of an assessment of the Szymanski model, it is important to evaluate the likelyhood of recurrent periods of dilatancy under extensional loading since it is so fundamental to this model.

In the following we shall focus on the conditions required for dilatancy in a medium, like that at Yucca mountain, that is heavily fractured and faulted. This, of course, is a precondition for recurrent large scale seismic pumping as a consequence of major earthquakes in that, without open fractures in the medium surrounding an earthquake failure zone, no very large scale water flow is likely to occur in response to the strain changes produced by the earthquake. Additionally, of course, the network of open fractures must be water saturated or partially saturated and interconnected.

We therefore first examine the conditions under which dilatancy in a fractured and faulted medium can occur and then evaluate the situation at Yucca Mountain relative to these criteria. The issues of water saturation and interconnection of open fractures at Yucca Mountain can, to some extent, be determined quantitatively using bore hole measurements of subsurface water levels and the permeability of the medium at depth. In this regard the water table and saturation levels are reasonably well established at Yucca Mountain, as is the high permeability of the medium to depths somewhat exceeding 1 km. Therefore, there already is field evidence that strongly implies high levels of fracture porosity and permeability at shallow depths, above one kilometer or so. However, showing, or at least providing a highly plausible argument, that much of the upper crust, to depths of a few kilometers at and near Yucca Mountain, is likely to be in a dilatant state is necessary in order to infer the likelihood and quantitative aspects of both seismic pumping and thermally driven convection in the upper crust following a major earthquake or nearby volcanic event. Thus, the argument for dilatancy must be such as to imply a highly dilatant state in order to infer connected fractures and high permeability for the medium at quite large depths, to 5 km. or so. †

Field Evidence Supporting Dilatancy and Seismic Pumping

Evidence of the existence of dilatancy is provided, in some circumstances, by direct observations of seismic pumping [26]. Sibson et. al. [22], in their paper on seismic pumping, cited the evidence of the Kern County California Earthquake of 1952, with a seismic magnitude of 7.7, where warm springs discharged directly from granite. Granites are dry rocks and such fluids as they may contain will be stored in fractures within the granitic body. The ejection of warm

† Soviet scientists (S.P. Kapitza, personal communication, 1990) have stated that rapid horizontal movement of water was observed at a depth of about 12 km. in their deep borehole drilling experiment on the Kola Peninsula. Thus, free water circulating at great depth, while previously thought by many geologists to be unlikely, may, in fact, be not unusual.

fluids from granite in the Kern County event is therefore evidence for seismic pumping from considerable depth and likewise supports dilatancy to such depths.

Reports given at the May, 1991 American Geophysical Union Meeting relating to the 1983 Idaho Earthquake [M = 7.3] provide other important, more recent, observations. Some of the observations reported in papers by Wood [23, 24] and Whitehead [25] indicate increased rates of discharge from many springs surrounding the epicenter and evidence of violent, large volume discharges near the epicenter. From Fig. 7 of Whitehead's paper, we note that starting in early November 1983 and including data up to August of 1984, it can be inferred that, in a period of 280 days, the total fluid flow was approximately (4×10^7) m^3. In addition, Wood comments that in the 6 months following the earthquake event, the total area affected produced an outflow of about 0.1 km^3 or 10^8 m^3. Moreover, when last reported, the flow rate was still extraordinarily high, so that the production of extruded fluid from all sources for a whole year is likely to be one, or perhaps two, orders of magnitude greater than that from the Matsushiro earthquake swarm, that is between 10^8 and 10^9 m^3.

Wood also made the point that "the major documented increase in groundwater discharges ... are from warm spring systems." This would suggest that the water is from relatively deep, confined aquifer systems. Indeed, from the temperatures observed, Wood suggests depths of the aquifers are from 0.5 to 2.0 km. Therefore it is reasonable to conclude that waters derived from such depths may be attributed to seismic pumping from a relatively deep dilatant zone.

Hence, the evidence of fluid flow from the granite of Kern County and that of the flow from Warm Springs in Idaho, among other sites including Matsushiro, clearly requires a conclusion that some earthquakes, of relatively high magnitude, can eject significant volumes of water at the surface as the result of seismic pumping. In this context "significant" means a volume of fluid of

10^6 m^3, or more, ejected as the result of an event of magnitude of about M wig7. Further, it can be inferred that the water flow is from relatively deep zones and most probably involves fracture flow.

Relationships between Laboratory and Field Evidence

The difficulties of interpreting the behavior of large volumes of rock using laboratory data are obvious. For example, a laboratory test specimen is usually reasonably homogeneous and isotropic. Large volumes of crustal rock are, almost invariably, neither homogeneous nor isotropic.

The differential stress necessary to induce failure in laboratory experiments designed to illustrate dilational behavior prior to failure may be 3-4 kbars, with a commensurately high stress-drop associated with failure. The stress-drop associated with natural failure on large faults is commonly reported to be about 100 bars, or less. These obvious differences between experimental and natural conditions and the disparity in the stress drop after failure in the two situations have been invoked to indicate the extreme difficulty, if not impossibility, of correlating the experimental results with natural events. While we acknowledge the difficulty of extrapolating from laboratory conditions to a field environment, we believe that it is incumbent upon us to do so; otherwise one's chances of correctly quantifying the mechanical response to natural seismic (and other) events becomes vanishingly small.

The large differences in the stress-drops of the laboratory and a typical natural event, for example, can be explained by recourse to known rock mechanic concepts and the application of common sense. The dilational experiments, at least to date, were conducted on "strong" dry rock. If the experiments had been conducted on saturated specimens with the fluid pressure set and controlled so that it is equal to the total least principal stress, then the differential stress at failure and the attendant stress-drop could easily be a factor of 3-4 lower than that cited above, so that the stress-drop in experiments which more correctly model crustal environments would be about 1.0 kbar, or even less.

It is also known that the strength of some rocks is related to the size of the volume of rock considered. For example, rock types, such as coals and shales which contain a large array of small fractures, exhibit a very marked decrease in strength with an increase in size. Thus, if the volume of the test specimens is increased by 8-9 orders of magnitude, the strength of the specimens is reduced by as much as 90 percent. The relationship between strength and "specimen" size for strong rocks is not known. However, in a rock mass with relatively few fractures it can be argued that the rate of decrease in strength with dimension of the rock mass will be smaller than that for coals and shales, so that in the crust the strength of a rock unit [with a low fracture density] may not be much smaller than that obtained in the laboratory under commensurate conditions of temperature, effective confining pressure and strain-rate.

Thus, even accounting for inherent fractures in-situ, the stress-drops inferred from modified small scale experimental data are still too large, in that they still exceed reported "natural" stress-drops by about an order of magnitude. However we note that the presence of water in rocks at elevated crustal pressures and temperatures leads to chemically related weakening of the rocks and this effect is not accounted for in the standard laboratory experiments. The weakening effects are accelerated by long term deviatoric stresses and high temperatures and can be expected to reduce the inherent strength of rocks, perhaps by as much as an order of magnitude.

Further, we would point out that the natural stress-drops are not "directly observed" but "inferred" and moreover these inferred values are "averages" for the whole of the various active fault zones which have been studied. In such fault zones it can reasonably be assumed that the stress-drop goes from near zero at the edges of the area of active displacement (or the stress may even increase) to some maximum positive value where the rock within the affected volume had a maximum resistance to shear. With such a distribution of real stress-drops, it requires little imagination to conclude that the interpretation of the average stress-drop associated with a real seismic event would not be greatly different from an "average stress-drop" one could calculate from an integration of the individual stress-drops, obtained in the laboratory, for the range [and relative proportion] of rock types and strengths associated with a natural seismic event.

Unfortunately, we are not able to ascertain, with accuracy, the exact types and variations of rock strengths involved in any natural seismic event. Similarly, the magnitudes of the principal stresses and the orientation of these stresses everywhere on the fault plane are not ascertainable. Consequently, we are reduced, at this time, to relatively simple models of natural seismic phenomena. In this regard, in the following sub-sections we will outline the experimental evidence regarding dilation and then apply these concepts to a model of re-shear on a fault. In this model we take slip on an existing fracture to be related to frictional resistance, in which we assume the stresses, which are not quantified, to represent the appropriate average stress conditions of both magnitude and orientation with regard to a planar fault. Such a model, while clearly very rough, is expected to be adequate for inferences of first order behavior at quite shallow depths in the crust.

Experimental Evidence Regarding Dilation

Experimental evidence relating to dilation of rock samples subjected to a differential stress is sparse, and takes the form represented in Fig. 35a. The deformation of the specimen is divided into four parts. In regions I and II the specimen experiences compressive volume change. The hypothetical extension of this path to the failure stress [f'] is represented by the

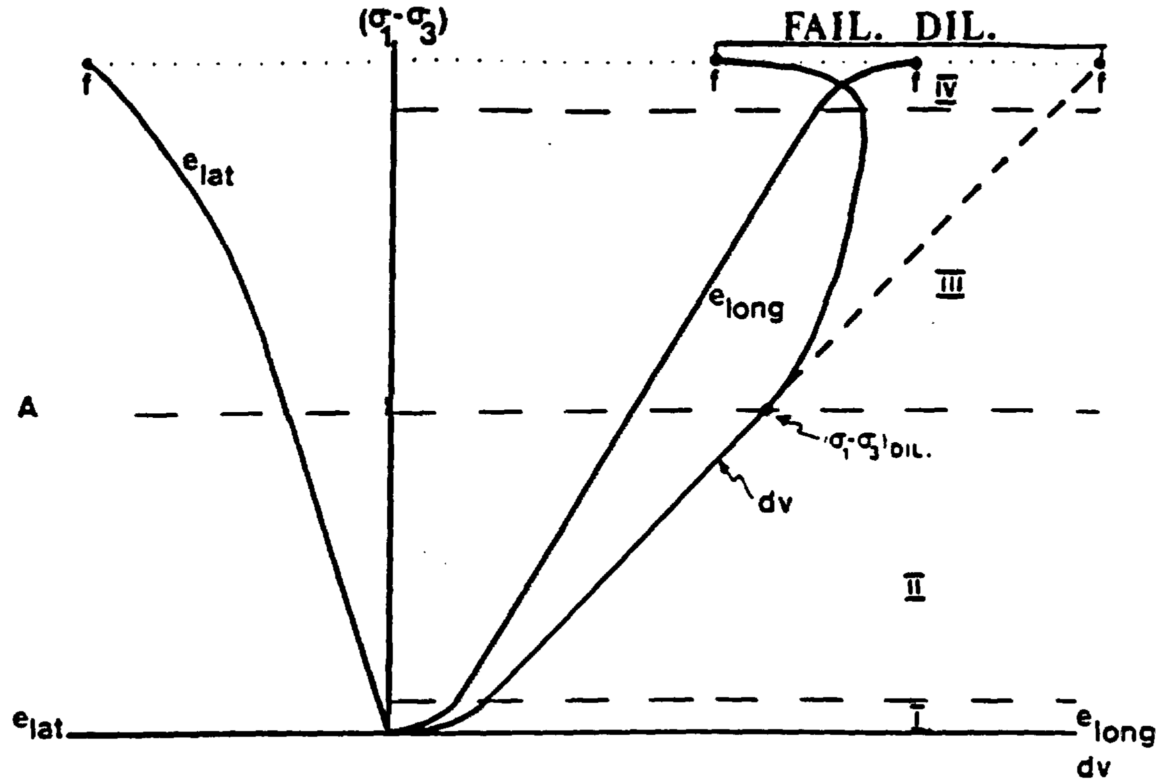
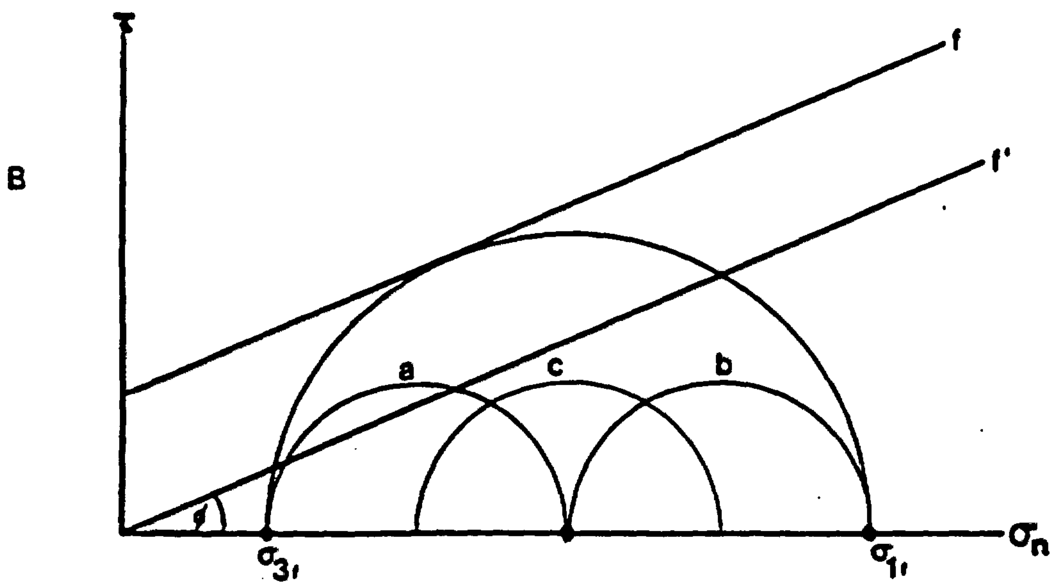


Fig. 35. - (A.) Qualitative representation of the stress/strain ($[\sigma_1 - \sigma_3]/e$) and stress/volume ($[\sigma_1 - \sigma_3]/dv$) relationships for a dry, cylindrical rock specimen at a confining pressure [σ_3] and subject to a progressively increasing axial stress [σ_1] until failure is induced [f]. Here: e_{lat} denotes lateral, i.e. circumferential, strain; e_{long} denotes axial or longitudinal strain. The notation: I, II, III, and IV denotes stages of deformation as defined in the text. dv denotes changes in volume of the specimen as deformation progresses; "Fail. Dil." denotes Dilation at failure; and $(\sigma_1 - \sigma_3)_{Dil}$ denotes the differential stress that marks the on-set of dilation. This stress is usually about half that required to cause failure.



(B.) Envelopes showing failure conditions for: [i] unsheared [f], and [ii] sheared rock, when, in the latter instance, the axis of maximum stress makes the ideal or optimum angle as defined in the text.

The differential stress required to cause initial failure [f] is [$\sigma_{1f} - \sigma_{3f}$]. Three smaller circles a, b and c, with magnitudes of half that required to cause the initial failure (i.e. these circles represent [$\sigma_1 - \sigma_3]_{Dil}$ in Fig. 35A) are also shown. The significance of these smaller circles is discussed in the text.

dashed line which continues into parts III and IV. However, estimates of the change in volume of the specimen, based on measurements of the longitudinal and lateral strains, indicate that at the boundary between II and III the decrease in volume of the specimen departs from the linear relationship which dominates in zone II. The rate of decrease in compressive volume change reaches zero at the boundary between zones III and IV and becomes markedly dilational in zone IV. The degree of total dilation is indicated by the horizontal line connecting f to f'. In experiments, the length of this line permits one to infer that the increase in volumetric strain is of the order of 10^{-4}.

The position of the boundary between zones II and III is likely to be specific to a given rock type. However, for our purposes it is sufficient to assume that this boundary occurs at approximately half the final failure stress. In Fig. 35b. the large stress circle represents the conditions necessary to induce brittle failure for an arbitrary, but representative, failure envelope in an intact specimen. The failure envelope for a suitably oriented shear plane, with zero cohesion, is shown as passing through the origin O. Three stress [semi] circles (A,B and C) are also represented. These have a diameter of half the failure conditions for the erstwhile intact specimen. That is, they represent the stress conditions when the boundary between zones II and III are attained. It will be recalled that, in the build-up from zero differential stress to the stress conditions represented by these three circles A,B and C, little or no dilation occurs within the rock specimen.

In Fig. 35b, it will be seen that circle A is tied to σ_{3_f}. This circle is incompatible with the failure envelope, so that re-shear would occur at a differential stress less than that shown by circle A. Hence, it can be inferred that for the situation in which the stress circle is tied to σ_{3_f} dilation of the specimen, prior to re-shear, will *not* take place. Similarly, if we take circle C, which is assumed to develop about the mean stress point, it will be seen in Fig. 35b that this stress circle is not quite capable of inducing reshear. If the differential stress is slightly increased, reshear will then occur and the specimen will experience a minute amount of dilation.

Only for circle B (anchored to σ_{1_f}) are the stress conditions well below that required for reshear. For reshear to take place when the stress circle is tied to σ_{1_f} the diameter must exceed that of circle B. Only for this condition will a modest amount of dilation take place prior to reshear.

It can be inferred that the stress circles A, B and C relate to the three main groups of faults. Circle A relates to re-shear on a Thrust, when the vertical stress is equal to the least principal stress; circle B relates to movement on a Normal Fault, when the maximum principal stress is equal to the vertical stress; and circle C relates to movement on a Strike-Slip fault, when the vertical stress is taken to be the intermediate principal stress (which is here assumed to equal $(\sigma_1 + \sigma_3)/2$).

If we may extend these experimental and theoretical concepts to field conditions, then the conclusions indicated above are in agreement with the statement that significant dilation of the country rock adjacent to an active fault can rarely be inferred from seismic data. Even if we take the example of circle B, the conclusion that a small amount of dilation will take place is compatible with the statement that such minor dilation is likely to be restricted to the zone adjacent to the shear plane.

The arguments set out above are based on conditions lacking in certain dimensions. For example, the junction between zone II and III may be different from that represented in Fig. 35a and the failure envelopes may have slopes which are different from those shown in Fig. 35b. However, adjustment of these quantities is not likely to result in a major change to the expressed conclusions. Hence, these conclusions, which also fit in with the statements made by some members of the geological and geophysical community, do not appear to augur well for the occurrence of dilation and earthquake induced seismic pumping. However, there is an in-built tacit and limiting assumption to the preceding arguments, namely that the orientation of the axis of maximum principal stress makes an angle [Θ] with the existing plane of weakness, such that

$$\Theta = 45^\circ - \phi/2 \qquad [1]$$

where, it will be recalled, ϕ is the angle of sliding friction. It is also a tacit assumption that the axis of intermediate principal stress is contained within the plane of shear.

Provided the rock in question obeys the Navier-Coulomb failure criterion, this relationship [given in Eq. 1] exists when the plane of weakness is initiated. However, it is a special case if the stress conditions satisfy Eq. 1 when the weakness plane experiences re-shear. It is to be expected that, more usually, the conditions required by Eq. 1 will *not* be satisfied. This is the general case, which we will now address.

Re-Shear on an Existing Fracture - The General Case

In the true general case, all three axes of principal stress can be oblique to the plane of shear. Here, we shall continue to assume that the axis of intermediate [or possibly least] principal stress lies in the plane of the fracture, so in reality we are dealing with a "restricted" general case.

If we assume that frictional sliding can be initiated by Amonton's Law, then it can be shown that if the axis of principal stress makes an angle [Θ], which does not necessarily satisfy Eq. 1, see [Fig. 36a] then [35]:

$$\sigma_1 / \sigma_3 = [1 + d] / [1 - d] \qquad [2]$$

where $d = [\sin 2\,\Theta + \cos 2\,\Theta.\ \tan\phi\ ] / \tan\phi$.

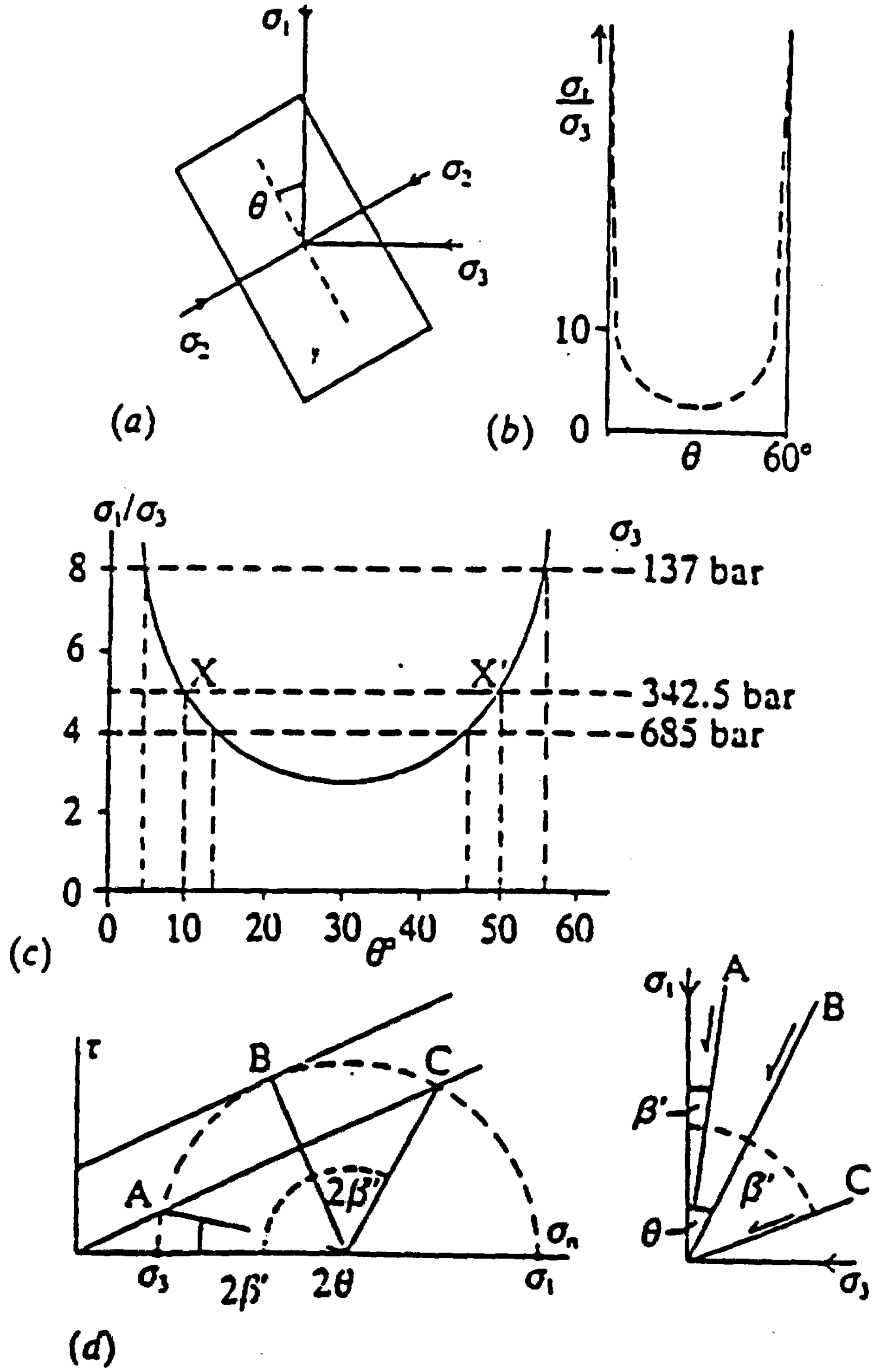


Fig. 36. - (a.) The existing fracture plane is shown, containing the axis of intermediate principal stress. The axis of σ_1 makes an angle Θ with the fracture plane.
(b.) The ratio of σ_1/σ_3 and the angle Θ that holds when slip on the fracture plane may occur.
(c.) For conditions in which $\sigma_3 \neq 0$, very high ratios of σ_1/σ_3 are not possible.
(d.) Failure conditions for specimens containing two planes of weakness (A and C) which make angles β' and β'' with σ_1 respectively. For these conditions, fresh fractures (B) may also form, which make an angle Θ with the σ_1 axis.

If we let $\phi = 30°$, then Eq. 2 can be expressed graphically as shown in Fig. 36b and c. It will be seen that the ratio of principal stresses goes to infinity at values of Θ of 0° and 60°. If the least principal stress is greater than zero, the curve shown in Fig. 36b is truncated as shown in Fig. 36c. For a value of $\sigma_3 =$ 342.5 bar, the limits, between which sliding is possible, are set at 10° and 50°.

What this means in terms of stress magnitudes and potential slipping on an existing shear plane can also be represented in terms of Mohr's envelopes [Fig. 36d]. If the fracture plane is oriented at an angle smaller than β' or greater than β'' to the axis of greatest principal stress, then the differential stress necessary to enable slip to take place on the plane of weakness is actually greater than that required to generate a new fracture plane. The situation represented in Fig. 36d is of two pre-existing fractures which are both exactly at the critical angles β' and β''. The stress circle necessary to rejuvenate these fractures is exactly equal to that which will initiate a fresh shear fracture [B]. Clearly, if a shear plane is oriented at an angle a little greater than β' or a little less than β'' the differential stress that will induce re-shear will only be a little less than that required to cause the generation of a new shear. Under these conditions, the pre-existing fracture will not take the form of a significant energy sink and the whole of the rock mass will experience dilation comparable with that represented in Fig. 35a. Thus, if a re-shear is induced on a pre-existing fault-plane which is oriented at close to either of the limiting angles [β' or β''] the differential stress needed to cause reshear on the fault will be so high that considerable pre-shear dilation will develop. Further, the collapse of this dilation, when re-shear occurs, could engender a significant degree of seismic pumping.

The question which must now be addressed is whether the major fault[s] adjacent to, or in the vicinity of, the Yucca Mountain Site are likely to meet the conditions of dilation and energy which will ensure the ejection of relatively large quantities of water from relatively deep crustal levels as the result of seismic pumping and thermally driven convection.

Stress Conditions and Possible Seismic Pumping in the Yucca Mountain Area

The important point to establish is the orientation of the axis of greatest principal stress relative to a fault plane likely to experience movement within the next few thousand years. In order to do so, let us consider the sub-parallel complex of faults formed by the Stage Coach Road Fault, and the Mine Mountain Fault Zone with its extension into Jackass Flats and the north-south trending faults which are probably second order structures associated with the first order Stage Coach Road Fault. (See Figure 7.)

The first order fault comes within a short distance of the proposed Yucca Mountain site, while some of the smaller, second order, N-S faults cut the site area, as shown in Figure 7b. The first order fault can be traced for about 30 km [see also plate 3.3.1 - 3. of the Szymanski Report] and trends almost exactly N42° E; though portions of the fault trace deviate from this bearing by a few degrees.

From the linearity of the first order structure and the angular relationship of the secondary faults, it is reasonable to infer that this major fault originated as a strike-slip fault and that the fault plane was approximately vertical. This fault, in the past few tens of millions of years, has almost certainly been modified to become a listric normal fault. However, as may be inferred from such deep fissures as Devil's Hole, within several kilometers of the surface the fault plane is still likely to be steeply inclined or even approximately vertical. As regards the second order, N-S trending faults, where these can be seen or inferred from surface topography, it is clear that these faults are also steeply inclined.

Let us now consider the probable orientation of the principal stresses in the upper regions of the crust [i.e. to a depth of several kilometers]. The orientation of the stress trajectories on a local scale, especially adjacent to faults, is likely to be somewhat variable from place to place. However, the regional stress trajectories will be largely determined by the current orientation of axes of principal strain-rates. the principal axis of extension is in the NW-SE direction. If we equate the orientation of the minimum principal stress with the regional axis of extensional strain-rates, it follows that the axis of the least principal stress makes an angle of approximately 90° with the mean trend of the Stage Coach Road Fault. In addition, in areas where topographical relief is low, the axis of one of the principal stresses will tend to be close to the vertical. This is a situation that may persist to depths of several kilometers. Also, since we are probably dealing with the analysis of a listric normal fault, the near vertical principal stress will be the greatest principal stress [σ_1].

Thus, we have the situation that both the fault plane and the axis of maximum spatially averaged principal stress are steeply inclined so that it is reasonable to conclude that this acute angle between them will indeed be very small. As may be inferred from Fig. 36d. this is one of the situations that ensures that movement can take place on the fault plane only if the differential stress is very large.

The two dimensional representation of the greatest and least principal stresses relative to the fault plane is shown in Fig. 37a-c. In Figure 37d we show the differential stress that is necessary to cause shear failure on a pre-existing fault plane when the axis of maximum principal stress acts at the "ideal" angle Θ_{ideal} [where $\Theta_{ideal} = 45° - \phi/2$, in our example this is 32.5°] and also when the angle between the axis of principal stress is 20° and 10° respectively. It will be seen that the differential stress required to cause shear on an existing fault plane, in this near sur-

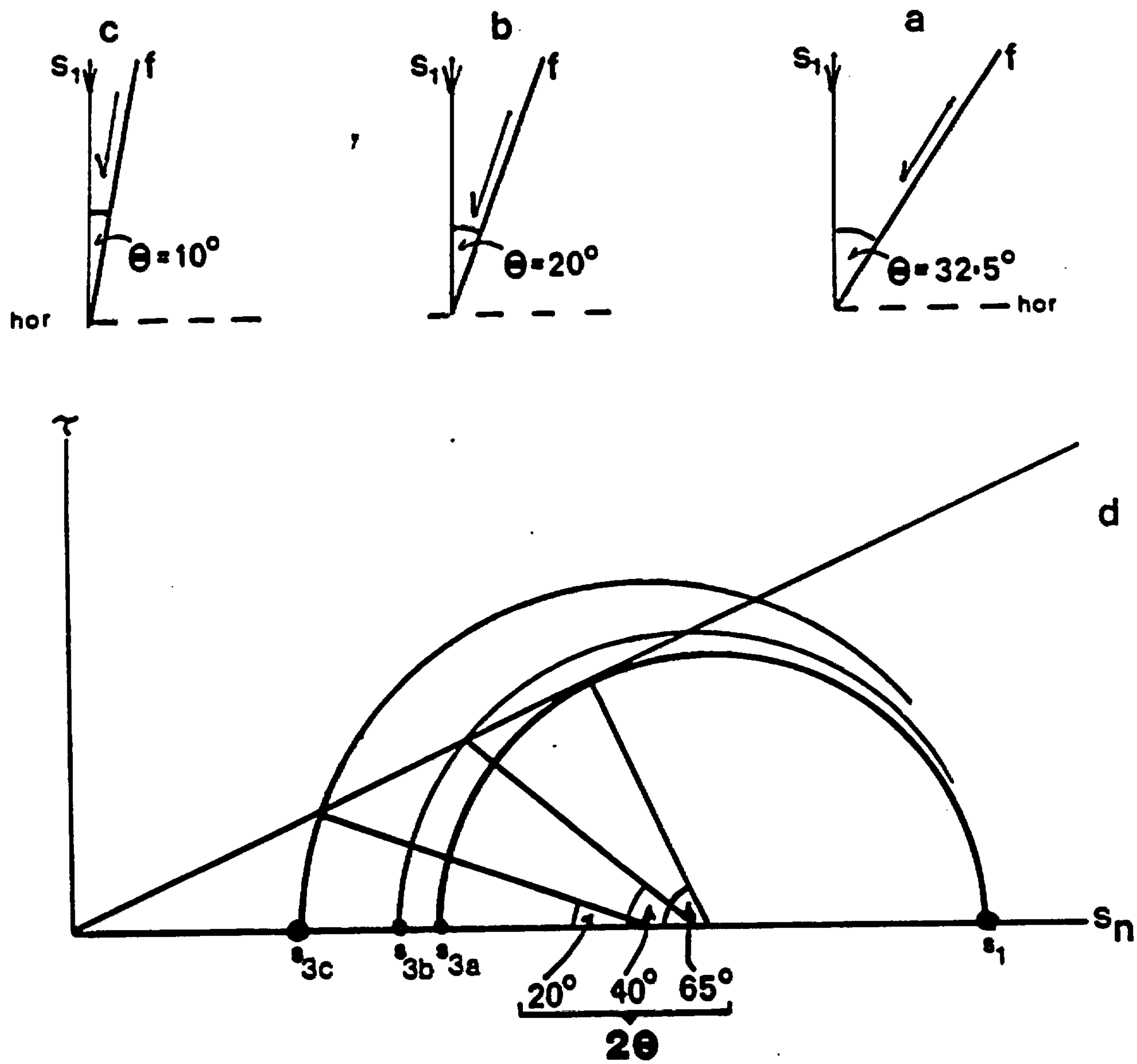


Fig. 37. - Inset diagrams a, b and c represent the orientation of a fault plane which is inclined to the vertical at angles of 32.5°, 20° and 10° respectively. It is assumed that the axis of σ_2 is parallel to the strike of the fault plane and, therefore, that σ_3 acts normal to the strike of the fault plane. The condition of $\Theta = 32.5°$ is such that the axis of maximum principal stress will cause failure at the minimum possible differential stress. This is represented by the circle $[\sigma_1 - \sigma_{3a}]$ in the main diagram which shows the possible stress conditions relative to the failure envelope for an existing fault. For values of $\Theta = 20°$ and 10° the stress conditions necessary to cause movement of the existing fault are given by $[\sigma_1 - \sigma_{3b}]$ and $[\sigma_1 - \sigma_{3c}]$ respectively.

It can be inferred, by reference to Fig. (36.) that, for small angles of Θ, the stress conditions necessary to cause failure on the fault are such that large dilation must develop in the adjacent fault blocks. The application of this concept to the Stage Coach Road Fault Complex is obvious.

face environment, becomes very large as the value of Θ becomes small. As we have seen, these conditions could well ensure that the region experiences a dilation of approaching 10^{-4} prior to a seismic event.

As regards the N-S trending secondary faults, these would have a comparable relationship between the axis of maximum principal stress and the inclination of the fault plane to that discussed above. Moreover, as may be seen from Fig. 38., one can infer that the least principal stress makes an angle of approximately 45° with the fault trend. Hence, the horizontal normal stress acting perpendicular to the strike of the fault plane would be significantly larger than that which the least principal stress would generate, if, as for the first order fault, it acted normal to the strike of the fault plane. Hence, the dilation associated with the second order faults immediately prior to their movement could be even larger than that experienced by the first order fault.

We note that if shear failure takes place along most of the 30 km. length of the Stage Coach Road Fault during a single event, a large earthquake [M>7.0] could result. In these circumstances (and comparing the probable effects of this future event with observed and inferred effects regarding fluid ejection after the Idaho earthquake of comparable magnitude), we submit that quite large quantities of fluids could be ejected in the vicinity of the Stage Coach Road Fault, and hence in the vicinity of the Yucca Mountain Site, as the result of seismic pumping. Further, one might also expect significant out-flow along the N-S trending secondary faults within the repository area proper.

Elsewhere, just to the north and east of the Yucca Mountain Site, the conditions regarding faulting are somewhat different from that at the site itself. Szymanski shows [Plate 3.3.1-5] near linear fault scarps which are the result of recent movements. The trend of these faults is approximately N-S. Moreover, within and to the east of the test site area, strike-slip movement is

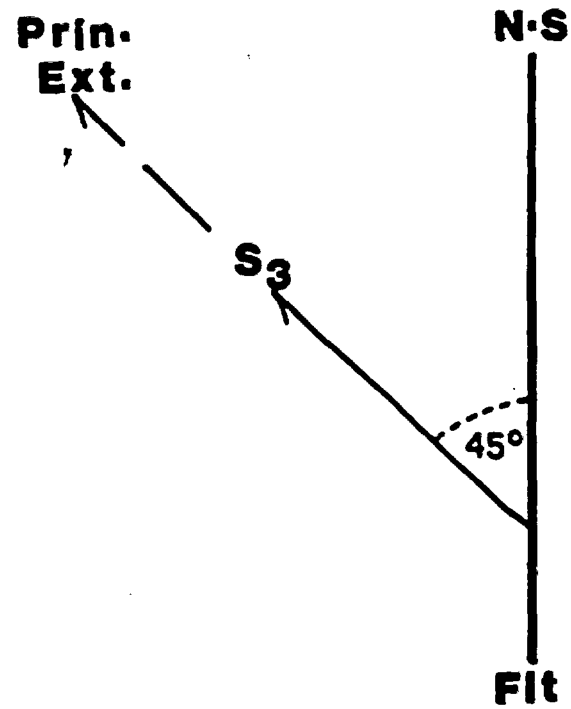


Fig. 38. - The orientation of the extension direction and, hence, the probable orientation of the axis of least principal stress is shown with reference to the trend of the N-S faults associated with the main Stage Coach Road Fault. One may infer that such an orientation of the least principal stress is far from the ideal, or optimum conditions, discussed in the text. Consequently, it is likely that movement on these faults will also be preceded by significant dilation within the adjacent fault blocks.

inferred on the basis of seismic data from nuclear tests [44]. Thus, it can be inferred that the extension direction in the Test Site and at Yucca Mountain is not uniform.

In some localities the least principal stress appears to trend 120-300°. From the orientation of the faults and the inferred orientation of the axis of maximum principal stress, it follows that known active faults can have orientations relative to the axis of horizontal principal stress that are likely to differ from the "ideal" situation, as defined by Eq. 1., by 10° or less. Assuming that the stress [semi] circle C in Fig. 35b. represents the conditions at which dilation will be initiated and that the dilation curve in Fig. 35a. represents the stress-dilatancy behavior for the rock mass in the nuclear test area, then it can be shown by simple constructions that the amount of dilation that will occur when the orientation between the maximum principal stress and the strike-slip fault differs from the ideal orientation by 0° and 10°, is respectively 0.06×10^{-4} and 0.10×10^{-4}. If we take the dilation that occurs when movement takes place on the Stage Coach Road Fault to approximate closely 1.0×10^{-4}, the dilations quoted above, for strike-slip faults, would be respectively 6.0 and 10.0 percent of that associated with the major normal fault.

We have noted that the depth to which the water-table may sink is likely to be related to the maximum degree of dilation that can be experienced in a spatial domain, since both the permeability and porosity, or storage capacity, would be related to the amount of dilation in the rock. Therefore, for the sake of argument, assume that dilation at Yucca Mountain is approaching the maximum value of 1.0×10^{-4} and that consequently the water-table is 500 m below a specific datum level. For the two degrees of dilation that may be exhibited in a region with strike-slip faults as cited above, the maximum level below the datum line the water-table may sink could be as little as 30 and 50 m respectively. Thus, this effect may contribute to the rapid changes in elevation of the water-table to the north and northwest of the site area.

In conclusion, we find that the existing stress loading and fault zones at Yucca Mountain are oriented in such a manner as to favor dilational behavior in the upper crust at Yucca Mountain. This inference is consistent with the limited pumping and flow data indicating fracture dominated flow at the Yucca Mountain site and is consistent with that part of the Szymanski model that involves medium dilation at a late stage in the evolution of the tectonic cycle. The results of this analysis, which indicate that dilation is to be expected under the circumstances at Yucca Mountain, also suggest that significant pressure and thermally driven flows can occur as a consequence of the altered strain state and fracture conditions in the medium following a tectonic event.

These inferences are compatible with Szymanski's model, but are not quantitatively discriminating. However, the magnitude of the flows that might occur can be estimated from past events occurring in similar environments, from modeling studies delineating the range of possible flows and from geologic evidence involving the volume and ages of water born minerals in the area; with each estimate carrying varying degrees of confidence. As part of this quantitative assessment, in the next section we consider the more precise estimates afforded by numerical modeling studies in an effort to determine whether the large volumes of water required by the Szymanski model can be transported from upper crustal depths to the surface.

VII. A Preliminary Quantitative Analysis of Some Aspects of the Hydro-tectonic Model

The two dynamical processes of greatest importance in Szymanski's CHT model, as illustrated in Figure 2, are seismic pumping and the late stage thermal convection. The quantitative characteristics of flows of these types, occurring in response to a tectonic event such as an earthquake, are clearly of importance in evaluating the viability of the proposition that groundwater may be forced into circulation over depth sections involving essentially the whole upper crust, that is to depths of over 5 km and over areas of the order of 100 km^2, by a large earthquake or volcanic event. Our interest is therefore in estimating, by quantitative means, whether flows of this sort, originating at earthquake hypocentral depths of from 5 to 20 km, can in fact produce high volume, high initial velocity flows from such large depths that will result in water moving all the way upward into near surface unsaturated zones and to the surface itself.

Our investigation is necessarily limited, due to constraints of time and resources, so we shall only investigate the seismic pumping phenomena that is one part of the response to the stress field changes from a tectonic event. Obviously, a theoretical investigation of the thermally driven convective processes that may occur as a second stage of flow in response to a tectonic event is of high priority, since the thermally driven flow is expected to be longer lasting and involve greater volumes of water. Indeed, the panel consensus position was that seismic pumping, is likely to be of secondary importance in terms of its influence on water table changes and mineral deposition. However, the long term thermal convection that might be stimulated by a tectonic event is more difficult to model, inasmuch as it will be initiated by nonlinear fracture production associated with an earthquake(s) and the subsequent pressure forced seismic pumping following immediately afterwards, during which additional fracturing due to gas and water overpressures may occur. In addition, changes in fracture patterns expose water to alternate distributions of rock temperatures and stored heat, which would inevitably stimulate vigorous thermal convection. Furthermore, to realistically model the phenomena both (CO_2) gas release from the water and chemical deposition must be included. In this connection, the state of modeling capability and general understanding of systems of this type has been discussed by Torgersen [28]. While it is, in principle, possible to incorporate these phenomena, it requires major expansion of current modeling programs and a very large, fast computer to perform the calculations for the long times required to obtain the desired understanding of the late stage response of the hydrological system.

Therefore, since the time progression of phenomena to be modeled is first the earthquake, then transient pressure forced (seismic pumping) flow and finally the late stage thermally forced convective flows, it is reasonable, as a first step in analyzing the magnitudes of the flow effects to be expected, to begin with a modeling study of the first two phases of the process - that is, the occurrence of a large earthquake and prediction of the nature of the seismic pumping. Accordingly, initial conditions for earthquake-induced processes are constrained by data derived from the contemporary system. We expect that if the seismic pumping is significant and involves vigorous flows from large hypocentral depths, then the second stage thermally driven flows would be similarly vigorous and depth extended. Consequently, at least a partial check on the quantitative aspects of the CHT model can be achieved.

The Geophysical Environment at Yucca Mountain

Since Yucca Mountain is in the Basin and Range Province, the environment is that of a tectonically active area that is undergoing extensional deformation. The crust and mantle structure at and near the Nevada Test Site has been quite extensively studied and is characterized by an upper mantle low velocity zone for both compressional and shear wave velocities and a relatively thin continental crust, as described, for example, by Archambeau *et al.* [43]. High heat flow in the region as well as a broad and pronounced gravity low, coupled with a variety of seismic data indicating unusually low compressional velocities in the upper mantle, strongly imply a partial melt zone just below the crust-mantle boundary which, on average, extends to a depth of about 200 km. As a probable consequence of the partial melt condition in the upper mantle, deep seated volcanism, with up-welling intrusions into the crust originating from the upper mantle, has characterized the region and has been particularly active near Yucca Mountain, with the last major phase ending about 10 million years ago. Relatively moderate, more recent activity has occurred in the adjacent Crater Flat area and resulted in eruptions producing cinder cones, some within about 10 km of Yucca Mountain.

Recent seismic surveys and tomographic studies (e.g. [27], [28]) suggest low compressional velocity zones in the middle crust, as well as in the upper mantle, at and near Yucca Mountain. Since compressional velocity decreases with increasing depth in a crustal or upper mantle depth section are most likely caused by partial melting, then the presence of such a zone very near or beneath Yucca Mountain implies the possibility of further volcanism originating from this crustal zone. Such volcanism would be different than that produced from the mantle in the past, and could represent a different phase of volcanism for the area in the future.

These conditions imply high crustal temperature gradients and generally high tectonic stress levels for the area as well as possibilities of modern volcanic activity. However, it is also known that the Basin and Range Province is highly heterogeneous, with crustal thicknesses varying rapidly, along with the thickness of the upper mantle low velocity zone and the observed heat flow. This implies that stress levels, thermal gradients and other variables, important in the present context, vary rapidly as well and that units as small as Yucca Mountain can have characteristics that are quite different at a single point in time than those considered typical for the province. For example, this variability seems to be manifested in the "source" and "sink" zones identified by Szymanski within the Nevada Test Site area, where the pressure and temperature gradients and water flows are quite different from one relatively small zone to another. Likewise, the rapid change in the water table level at the north end of Yucca Mountain implies an adjacent zone in a very different state than that found at Yucca Mountain. As previously noted, this may be due to a change in the tectonic stress state, with the main part of Yucca Mountain in an extensional environment with normal, dip-slip or listric faulting, while to the north the deformation and faulting is surface parallel shearing (strike-slip faulting).

In terms of the characterization of Yucca Mountain for earthquake and flow modeling purposes, the most important properties are the tectonic stress state and the hydrological properties of the medium; that is, the natural and fracture porosity and permeability of the medium. Within this relatively small geological unit, we expect these properties to be only mildly variable laterally, at least away from the major faults, but quite strongly variable with depth in the upper crustal zone to be modeled. As was discussed in detail in the preceding Section VI, we expect the medium to be in a dilatant state and the faulting to be produced by any large earthquake to be dip-slip or listric, with stress drops in the moderate range from 20 to 50 bars. Thus, the medium porosity and permeability is expected to be controlled by open fractures to considerable depth (i.e., to the "Z surface" at about 1.5 km), with predominantly vertical fractures and, consequently, highly anisotropic permeability. That is the permeability in the vertical direction is expected to be much greater, by about an order of magnitude, than that in the lateral direction, perpendicular to fracture surfaces. Likewise, the fracture porosity is assumed to dominate over natural porosity and to be, on average, high (10^{-3} to 10^{-4}) at shallow depths and to decrease the "Z surface".

The initial thermal state of the medium can be characterized by relatively high gradients and temperatures, which are in keeping with the situation in the Basin and Range as a whole, but with strong variability in the temperature gradient with depth, as is observed at Yucca Mountain. However, while the thermal state would be very important in modeling the late stage thermal convection, it plays no essential role in modeling the pressure forced seismic pumping that will be considered here.

What is important for the seismic pumping, however, is the role of CO_2 gas that could come out of solution when the water pressure in fractures is reduced below ambient in response to the stress changes produced by an earthquake. In particular, at Yucca Mountain we expect the water at great depth to contain considerable amounts of CO_2 in solution due to the history of local volanism and to the presence of the thick Paleozoic limestones beneath the overlying tuffs. Since CO_2 would come out of solution when the pressure drops below the ambient level, then degassing of the water can occur. Subsequent increases in pressure will not readily force the CO_2 back into solution, so that once released the gas remains as a second phase component along with water. Therefore dynamical fluctuations in pressure during an earthquake, which can be very large, can produce significant CO_2 which will, by itself, pressurize the fracture system and will flow at high rates, pushing water with it. Additionally, the water will produce additional gas as it moves upward into a lower pressure environment, so that this entire process can produce very energetic gas-fluid flow phenomena.

Continuum Equations and Approximations for Earthquake Stress Changes and Gas-Fluid Flows in a Fractured Medium

In considering the full complexity of the problem of modeling both the dynamics of earthquake failure and the gas-fluid flow that can take place in the surrounding water filled fractured medium, we conclude that as a first step it is appropriate to model only the flow effects to be expected from the final stress changes due to an earthquake. That is, the strong dynamical stress fluctuations accompanying a rapidly growing failure, which will likely be very efficient in driving CO_2 gas out of solution, will be neglected in this preliminary investigation. Thus, only the final, static changes, in the stress field will be considered in the process of pressure drive flow and degassing. In this case, if the dilatation in the rock locally increases due to the event, then the fluid pressure in fractures would be reduced below the initial ambient level and CO_2 will come out of solution in direct proportion to the pressure reduction from ambient. Hence gas will be produced, but not nearly as much as would be produced by the strong fluctuations in the dynamic pressures. That is, while the dynamical fluctuations would not have much direct effect on the fluid flow in fractures, due to inherent inertial effects in the fluid flow mechanics, they would have a large and important effect on gas production. Neglect of this dynamical effect, and only accounting for late time (static) pressure changes, will therefore produce a minimum amount of CO_2, but nevertheless will provide an indication of the gas flow effects that can occur. In this case, however, we will get a "lower bound" estimate of the gas production and flow.

Another effect that is related to gas production is new fracturing, or pre-existing fracture opening, that can occur as a consequence of gas production. In this preliminary study we will not incorporate fracture failure conditions, except along the zone of primary earthquake rupture, or conditions for fracture re-opening, into the dynamics of the flow process in the fractures and will hold the fracture porosity and permeability fixed. Therefore we also neglect the important effect that gas production, and water pressures, can have on new fracture production and enhancement of permeability in areas where gas is released and fluids are pressurized, which occurs during both the transient phase of failure zone growth and as a consequence of the final (equilibrium state) stress changes produced by the earthquake. This also will give us a "minimum" estimate of the resulting flow rates and volumes.

Therefore, we will consider only the final stress changes in the rock matrix due to an earthquake acting as the driving force for the pressure forced flow in the fractured system. We account for CO_2 production by allowing degassing in proportion to the pressure drop in the fracture water below the ambient, but do not account for fracture opening and permeability changes, so tnat the permeability of the system remains fixed during the ensuing pressure forced flows. Degassing will occur where the earthquake induced dilatation in the rock increases, and pressure forced water and gas flows will occur in directions away from areas where the rock dilatation is decreased by the earthquake (where pressures on the fracture water are increased).

As noted earlier, the medium is considered to be in a dilatant state with most fractures oriented vertically, and this condition will be incorporated in the modeling. That is, the permeability in the vertical direction will be taken to be of the order of ten times that parallel to the earth's surface and perpendicular to the fracture surfaces. We can, of course, vary this condition to check the sensitivity of the predicted flows with respect to this anisotropy.

The flows to be modeled, therefore, are two phase water and gas flows which are induced by dilatation changes in the rock that change the pressures on the water (and gas) in the fractures. The earthquake induced stress changes that will be used are those representing (only) the equilibrium field changes and consequently can be adequately described in terms of stress changes produced by a dislocation of the medium due to some specified offset along a fault plane. This representation of earthquake induced stress field changes is easily calculated for quite general cases by finite element or finite difference methods. We show some of the rather standard results for particular cases of dip-slip and listric faulting in a medium appropriate to

Yucca Mountain in the next sub-section. These results provide the "driving" pressure field on the water to produce the degassing as well as the water and gas flows in the medium.

The modeling of the water-gas flows in the fractured medium are not nearly as straightforward however. Here we note that the flows are through a fractured system and the usual approximations for seepage flow using Darcy's law in the context of a mixture theory formulation is not expected to be a good representation. Instead, we believe that a much more realistic approximation can be achieved by including the Darcy type drag forces on the water or gas flows, due to fracture geometry changes and viscosity coupling to the rock at the fracture boundaries, as an equivalent body force term in the equations of motion for these two constituents. In this case we can approximate the effects of changes in fracture geometry (e.g. branching, curvature and constrictions in width) by introducing random spatial fluctuations in the drag coefficients and simultaneously represent, by other spatial variations in the drag force coefficients, the effects of larger drag along the fracture surfaces than in the interior of the fracture.

The formulation of the flow problem is now simply given by the conservation equations for a multi-component flow of a (viscous) fluid, which can be a gas or a liquid, or both. The conservation of mass for the *nth* constituent of the flow is:

$$\frac{\partial \rho^{(n)}}{\partial t} + \frac{\partial}{\partial x_j} (\rho^{(n)} v_j^{(n)}) = r^{(n)} \tag{1}$$

where the summation convention applies to repeated (spatial) indices that are not enclosed in parentheses. Here $r^{(n)}$ is the rate of production of the *nth* constituent, and $\sum_n r^{(n)} = 0$. Conservation of momentum for each component is:

$$\rho^{(n)} \left[\frac{\partial v_j^{(n)}}{\partial t} + v_k^{(n)} \frac{\partial v_j^{(n)}}{\partial x_k} \right] = \frac{\partial}{\partial x_i} P_{ij}^{(n)} + F_j^{(n)} \tag{2}$$

where $F_j^{(n)}$ are the external forces on the *nth* component and is taken to include the gravity forces and the (equivalent) drag forces. Here $P_{ij}^{(n)}$ is the generalized stress, which normally includes viscosity effects in the *nth* component material. Here the drag force equivalent will be taken to have the form:

$$_dF_j^{(n)} = \sum_{m \neq n} \alpha_{jk}^{(n,m)} \left[v_k^{(n)} - v_k^{(m)} \right] \tag{3}$$

where the $\alpha_{jk}^{(n,m)}$ is the drag coefficient tensor between the *nth* and *mth* constituents and consists of spatially variable randomized functions, while $v_k^{(n)}$ is the *kth* particle velocity component of the *nth* constituent.

The conservation of energy can be put in the form:

$$\frac{\partial}{\partial t}(C_v^{(n)}T^{(n)}) + v_j^{(n)} \frac{\partial}{\partial x_j}(C_v^{(n)}T^{(n)}) = \frac{\partial}{\partial x_j}\left[K_{jk}^{(n)} \frac{\partial T^{(n)}}{\partial x_k} \right] - p^{(n)} \frac{\partial v_j^{(n)}}{\partial x_j} + \Phi^{(n)} \tag{4}$$

where $p^{(n)} \equiv P_{kl}^{(n)}\delta_{kl}$ and $\Phi^{(n)}$ represents the sum of viscous dissipation and energy exchanges between constituents due to the interactive drag forces. Also, in Eqn (4), T is the temperature; $C_v^{(n)}$ is the specific heat at constant volume and $K_{jk}^{(n)}$ is the thermal conductivity tensor, which is taken to have the isotropic form $K_{kj}^{(n)} = \kappa^{(n)}\delta_{kj}$.

In the fundamental equations, (1) through (4), the dependent and independent variables are normalized with respect to typical values. In particular, distances are normalized through the characteristic depth which is of the order of 10 km here. Velocities are normalized with respect to c_s, the sound velocity in water at the Earth's surface. Similarly, density, pressure and temperature are normalized to surface values, and the independent variable, time t, is normalized by using the standard depth and velocity. As usual, dimensionless ratios are obtained by this process, whose magnitude is a measure of the relative importance of the terms in the basic equations.

The equation of state for the gas is taken to be ideal, that is

$$p^{(1)} = \frac{k_B}{m^{(1)}} \rho^{(1)} T^{(1)} \tag{5}$$

where k_B is Boltzman's constant and $m^{(1)}$ is mean molecular weight of the gas, taken as component 1. Because the water is relatively incompressible, any gas present will dominate the pressure terms for both gas and water, so that this equation of state will dominate both components and will depend on the amount of gas present initially and that released through decompression of the water.

The equations can now be split into two sets, one governing the ambient field, with the other representing the transient flows due to sudden stress changes. The ambient field is that of a water system under hydrostatic pressure gradients with zero velocities. In this case it is assumed that very little gas is present, except as dissolved in the water initially. This ambient solution gives a hydrostatic pressure gradient which balances the gravitational forces and is readily removed form equation (2), leaving similar equations for the transient flows of each component.

The resulting set of non-linear partial differential equations are converted to a corresponding set of finite difference equations for computer integration in time and space. Upwind differencing is used for first order spatial gradients with the advection velocity terms acting at the upswing point. However, if the velocity operates on its own velocity gradient, such non-linear terms are treated non-locally on the lattice for stability.

The updated velocity variable is projected not from just the old dependent variable, a process that is inherently unstable, but from a distributed smooth average of the variable at locations surrounding the specific spatial location and such a smoothing method brings stability to the differencing scheme. It also helps in stabilizing the integration at grid corners and boundaries. Numerical diffusion is produced by this process, but is constrained by having no smoothing of the density variable while allowing velocities and temperature to be smoothed sufficiently for long-term stability, given a sufficiently small time-step. The second order derivatives in the viscosity and thermal conductivity items are modeled by finite differences taken at the surrounding spatial locations. In the integration scheme, the velocities, flow temperature and density are obtained from integration of their continuity equations. The governing pressure is obtained from insertion of the updated gas density and temperature into the ideal gas equation.

Pressure Driven Flows (Seismic Pumping) in Response to Equilibrium Stress Field Changes From Large Earthquake

Figure 39 shows cross sections of displacement, stress and dilatation fields produced by two slightly different kinds of earthquakes, as modeled by a finite element computation. A uniform one meter offset on a failure plane was used to produce stresses and displacements in the medium. The earthquake hypocenter is at 12 km depth and is unilateral, propagating from this depth to the surface. The grid extends 40 km in depth and 80 km wide. The important field variable, in terms of pressure forced flow and degassing, is the dilatation, which is plotted in the lower left panel in the set for each earthquake type. Since the negative of the rock dilatation is proportional to the pressure on the fracture water, zones of increasing rock dilatation (colored red) correspond to decreases in pressure in the fracture water, while decreases in rock dilatation (blue) is the opposite. In zones of increased fluid pressure (blue), the fluid will be forced to flow in a direction from higher to lower pressures, i.e. along the maximum gradient, and will, in so doing, reduce the pressure on the fluid and its gradient. Regions of increased dilatation (red) are zones of reductions in water pressure and degassing of the water. Thus, these are zones of CO_2 production.

We note that the listric fault produces a more complex pattern in all the fields but particularly in the rock dilatation. This will manifest itself in a somewhat more complicated pattern for

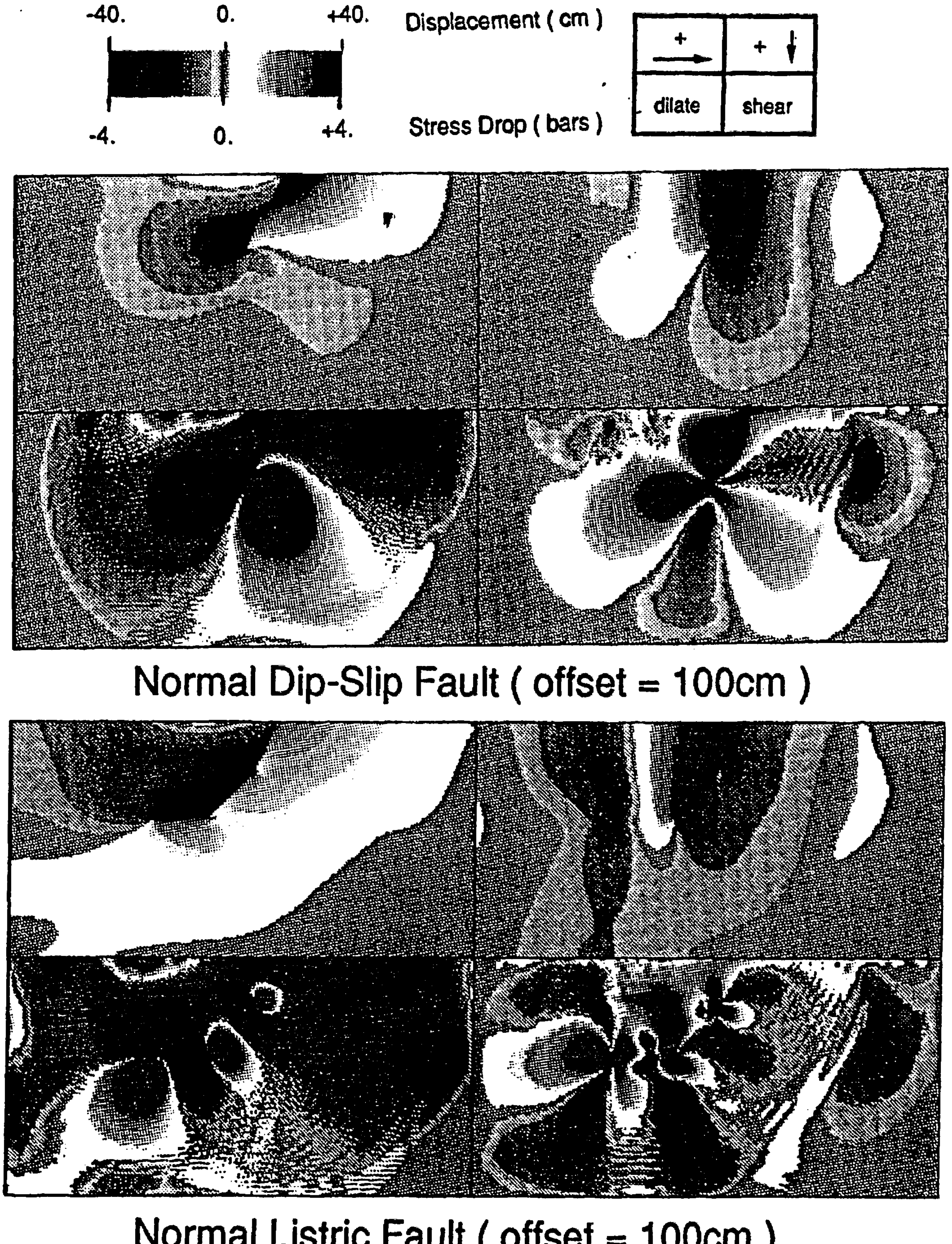


Fig. 39. - Displacements, shear stress and dilatation in the upper crust in the vicinity of a dip-slip (60°) and a listric (60° to 0°) fault with hypocenters at 12 km. depth. The inset at the upper right indicates the field variable plotted for each fault type in the four vertical cross-sections shown. (Horizontal and vertical displacements, dilatation and shear stress.)

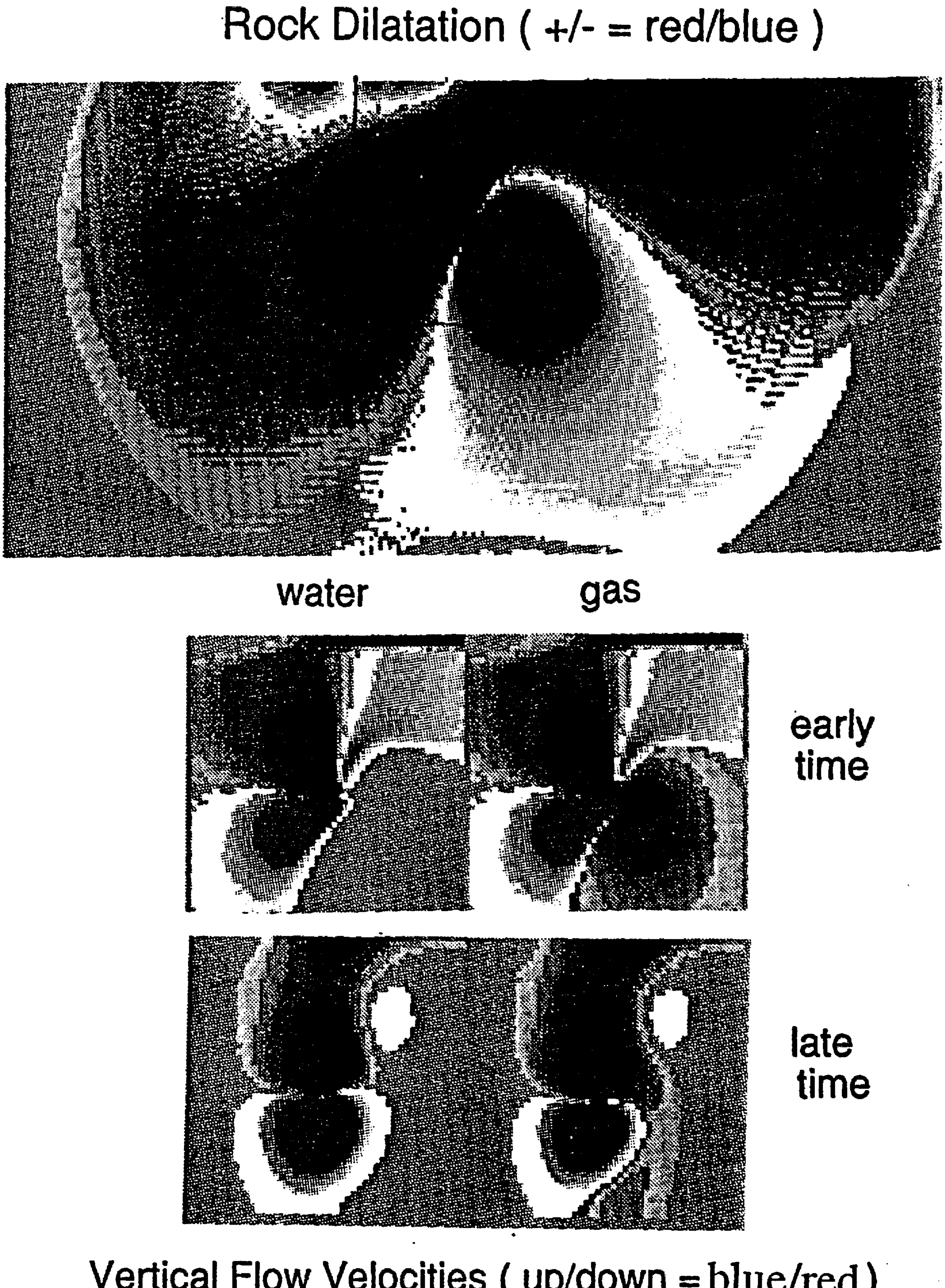
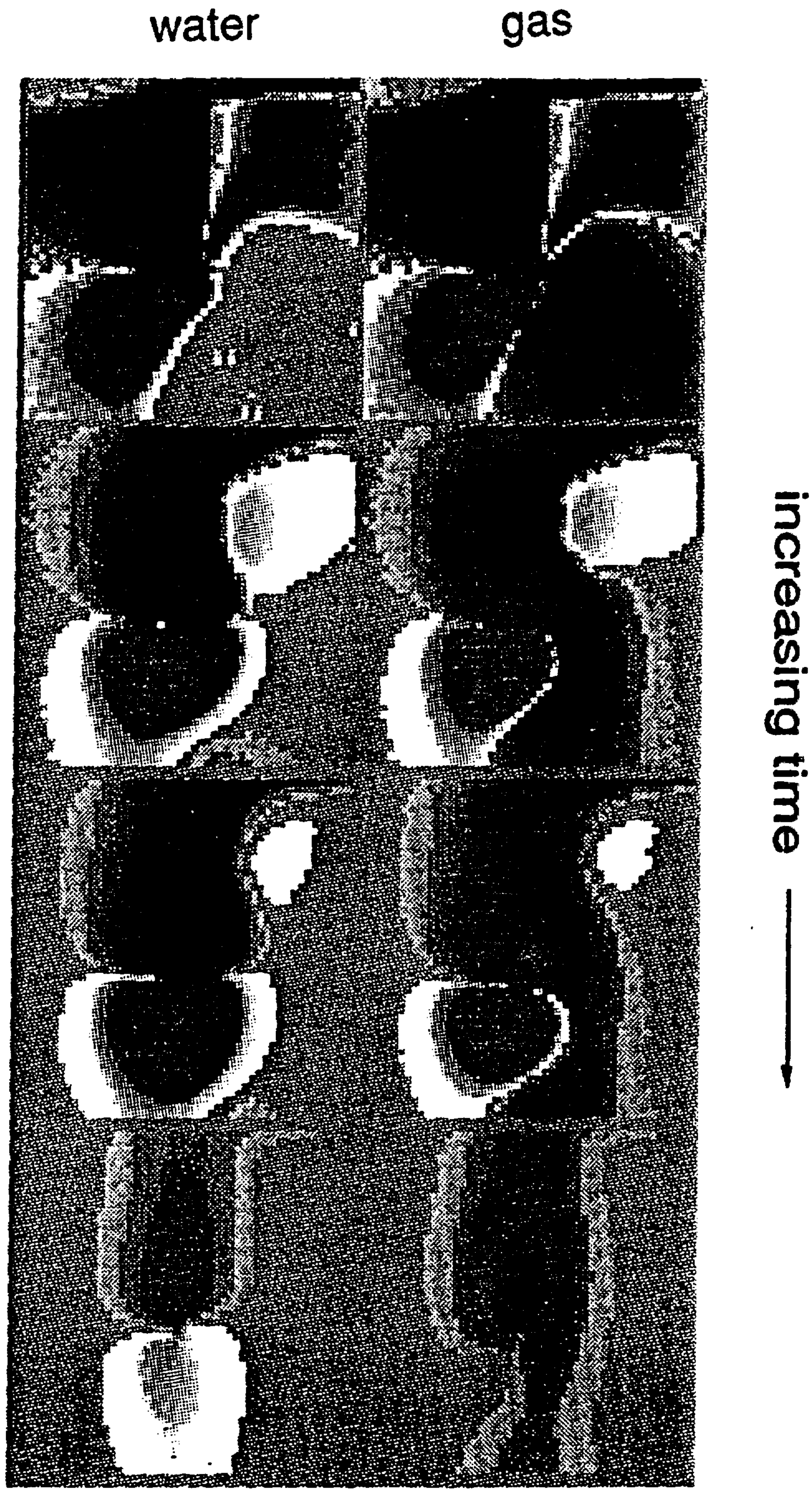


Fig. 40. - Dilatation of the medium due to a dip-slip fault (1 meter fault offset, magnitude about 6) and predicted water and CO_2 gas vertical flow velocities at early and later times.

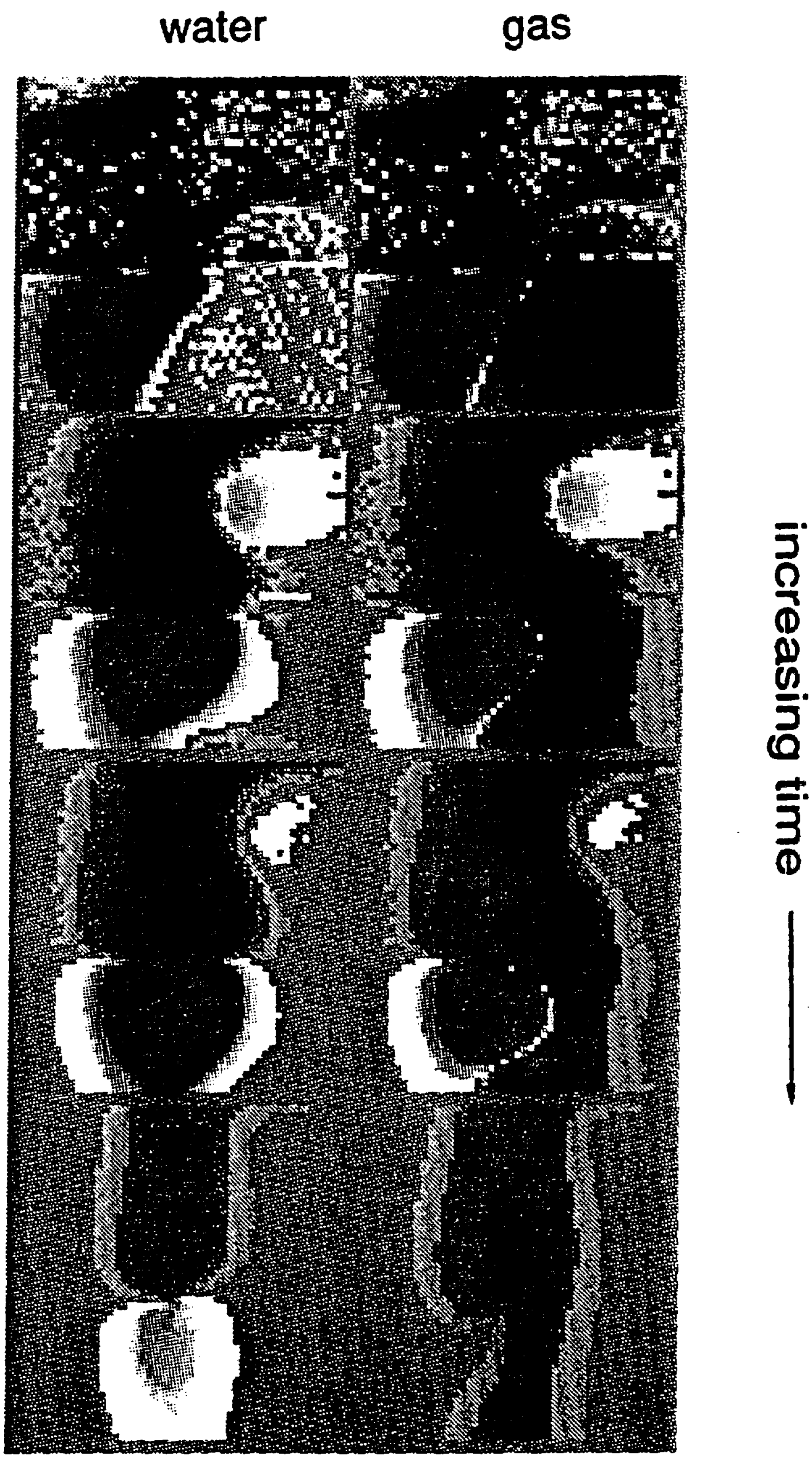
degassing and water-gas flows.

Figure 40 shows the dilatation pattern in cross section for the normal, dip-slip earthquake as well as depth cross-sections of the water and gas flows produced when the permeability is about 1 milli-Darcy and the porosity is 10^{-2} to 10^{-3}. The square outlined in this top panel (20 km by 20 km) shows the region of flow in the lower panels. As indicated, the early time water flows are upward from the ("hanging wall") area adjacent to, but above, the dipping fault plane and the highest upward particle velocities are just above the hypocenter of the earthquake. In the region below the fault plane (the "foot wall"), the water pressure is reduced and there is little flow, except just below the zone of upward flow. In this area the particle velocity direction is downward, with the water being supplied at the interface between these zones by lateral inflow, primarily into the plane of the cross section shown. At later times, as illustrated in the lower panel, a simple pattern of an upward moving column of water flowing to the surface as indicated (by the blue zone) while below it the flow is downward. The horizontal components of the flow velocity field converge into this zone to provide the necessary fluid mass for the divergent "up and down" vertical flow. This divergence corresponds to cellular flow patterns above and below the failure plane that have opposite vertical velocity directions where they meet along the fault plane. These "cells" extend from the hypocentral depth, at 12 km in this example, to the surface and from below the hypocenter throughout the crustal zone, although the flow rates are very low in the deep crust. An essential point is that the water flow is widespread throughout much of the crust and in particular involves upward flow from the mid-crust hypocentral depth to the surface. Decreases in the permeability reduce the flow rates but the patterns of the flows are about the same. Decreases in fracture porosity can increase flow rates, but the total volumes of water carried upward by the flow remains about the same so long as the porosity does not get very low, below about 10^{-4}.



Fluid Flow Rates Along 20kmx20km Depth Section
(blue/red = up/down at 0.1m ^{3}/s-m ^{2} of plan)

Fig. 41. - Water and CO_2 gas flow histories in a (pre-dominantly) vertically fractured crustal section shortly after the occurrence of dip slip faulting resulting in an earthquake of magnitude of about 6.



Fluid Flow Rates Along 20kmx20km Depth Section
(blue/red = up/down at 0.1m ^{3}/s-m ^{2} of plan)

Fig. 42. - Water and CO_2 gas flow histories in a fractured crustal section as in Fig. 41., but with a randomized drag coefficient.

The CO_2 gas flows shown in the right side panels are similar in their general character to those for the water except that upward flow occurs below the fault plane near the hypocenter as well as above it. This is due to the release of gas from solution in the zone of increased rock dilatation, where the pressure on the water is therefore reduced. In this zone gas buoyantly wells up of this gas occurs and results in the flow pattern shown. At late times the gas flow is nearly identical in its spatial pattern to that for the water, except that higher particle velocities are involved.

Figure 41 shows a longer time span of the same water and gas flows. At later times the gas flow, in particular, is upward moving throughout the section shown, which extends to depths of 20 km. The water flow, at yet later times than that shown, also is upward through the depth section, but has lower upward velocity values than that for the CO_2

Figure 42 again shows the flow response to the earthquake but in this case the drag coefficient in equation (3) has been heavily randomized. The effect of this randomization manifests itself in the early stages of the water and gas flows but is rather rapidly overwhelmed at later times by the forced uniformity in the flow patterns due to the (relatively uniform) pressure distribution patterns produced by the earthquake. Obviously, more complex patterns can easily be produced by introducing strong spatial variability in all the material properties, including elastic properties, so that a wide variety of variability in these basic patterns can be expected. However, the general characteristics of these predicted flows persist. In particular, circulation of water and gas from very great (hypocentral) depths can be expected if the fracture porosity and permeability persist at a modest level throughout a major portion of the crust.

In the examples shown, the (effective) permeability was taken to be uniform along the crustal depth sections involved in the model calculation and of moderate level (about 1 milli-

Flow Rates for Emerging Water (per meter of fault length) Following an Earthquake of M ~ 6.

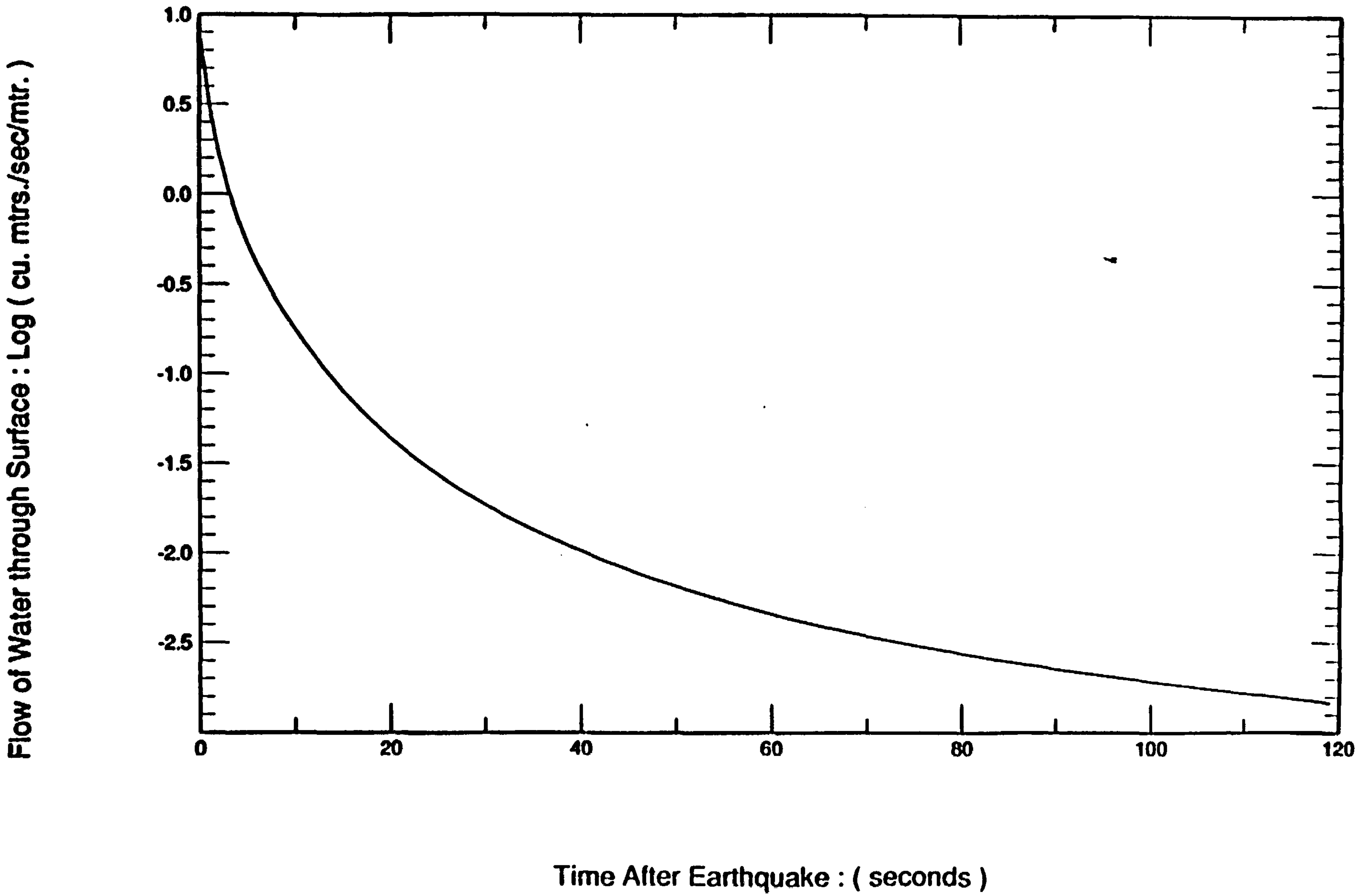


Fig. 43. - Vertical flow rate versus time for water upwelling at the saturated unsaturated zone boundary in the vicin-

Flow Rates for Emerging Gas (per meter of fault length) Following an Earthquake of M ~ 6.

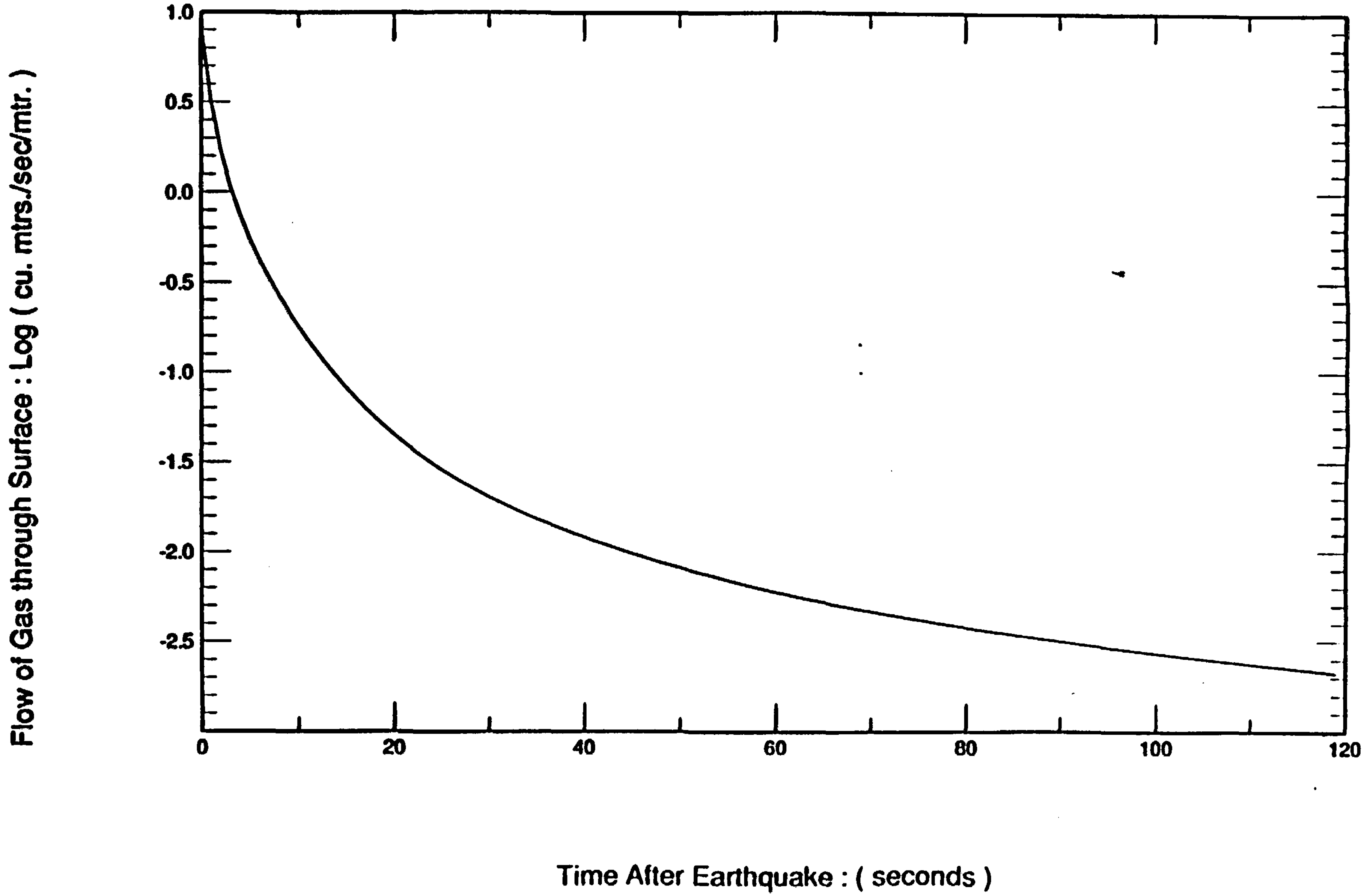


Fig. 44. - Vertical flow rate versus time for CO_2 gas at the saturated-unsaturated zone boundary for the case described in Fig. 43

Darcy). Much lower average levels and spatial variability reduce flow velocities but, for a fixed fracture porosity, do not much change the total volume of flow when integrated over a long period of time, so long as the porosity is in the range from 10^{-1} to 10^{-4}. For porosity values from below 10^{-4} to 10^{-5} the flow volumes begin to be limited by porosity. However, only for rather large depths, below 5 km, do we expect lowered fracture porosity along conduits in tectonic areas. In this regard, we again note that the deep Kola Peninsula bore-hole in the Soviet Union showed horizontal water flow at its greatest depths, near 12 km. Further, similar determinations and inferences of very deep water circulation have been made in various other areas in the world (*e.g.* [30]-[32]) so that relatively high levels of permeability and porosity at upper and mid-crustal depths clearly occur and these occurrences are not just confined to tectonic areas like the Basin and Range Province.

An important quantitative aspect of the flows modeled is the flow rate through the upper surface. In the calculations shown in Figures 40-42, this upper surface would correspond to the top of the saturated zone. In this regard, Figure 43 and 44 show the flow rates for water and gas in cubic meters per second per meter of fault length perpendicular to the cross section of Figures 40-42.

These plots show that the flow rate for both water and gas is very high in the first few seconds and drops off quickly to a near constant level after a few minutes. The rates for the gas flow are seen to be uniformly higher than those for the water. If we use about a 10 km fault length as appropriate for a magnitude 6 1/2 earthquake (with a stress drop around 20 bars and a one meter fault offset) then we can estimate the amount of water (and gas) that can be expected to be "pumped" into the unsaturated zone. Based on the asymptotic rate levels at late times, we get about $10^6 m^3$/year of water for this particular case. Gas volumes at atmospheric pressures would be about 3 to 4 times as high. For a larger event, with a magnitude around 7, we estimate volumes of water between 10^7 and 10^8 m^3/year. These values are in the range of those observed, for example for the Borah Peak earthquake.

Depending on how the water flows within the unsaturated zone such pressure forced water flows could result in a rise in the water table. However, we would expect the flow to be more channeled in this zone and to flow upward along fault zone conduits and reach the surface at isolated locations. Thus, an estimate of the rise in the water table for this pressure forced initial flow would be complicated by this expected surface outflow and run-off. In any event, the major rise in the water table would be expected to occur over the much longer period of thermally driven flows. However, if an area of about 100 km^2 encompassing Yucca Mountain is involved in seismic pumping of the sort described here, then using the estimates obtained for the total volume flow over one year, one gets a water table rise of about 500 meters if the unsaturated zone porosity is uniformly near 10^{-3}, and of about 50 meters if it is near 10^{-2}. Here we assume, as in the modeling described earlier, that the horizontal permeability in the plane of the cross-section analyzed is about an order of magnitude lower than the vertical permeability.

VIII. Possible Consequences of Water and Gas Intrusion for Repository Containment

A number of U.S. government reports [2.3] describe design features of the repository proposed for Yucca Mountain and include preliminary calculations of the thermal state of the surrounding rock medium after emplacement of the units. Since the plan is to place the high level waste in the site without much of a cooling period before emplacement, they are quite "hot" and produce rather high temperatures in the medium. The calculations indicate that the cannisters would reach 250°C and the surrounding rock temperatures would average around 120° to 130°C, depending on thermal parameters used in the computational estimates. The repository zone would remain this hot for several hundred years, and would only very slowly cool down with time. Thus, since the thermal energy stored in the medium surrounding the repository is large and because of the high temperature differential between the rock mass and the vaporization temperature of water under normal pressure conditions, the waste heated rock is a potential source for steam generation during water intrusion.

In particular, if rapid extrusion of water from depth were to occur, such as by "seismic pumping" which has been documented for a number of earthquakes of the type expected at Yucca Mountain, then large volumes of water and gas (CO_2) could be injected into the heated repository area. One could then expect some conversion to steam resulting in pressurization of the tunnel system, a rise in the vaporization temperature leading to the presence of super-heated water and the creation of a very corrosive environment that could cause rapid break-down of the waste containers.

In addition to steam, it would be expected that CO_2 gas flows would normally accompany any incidence of water up-welling at Yucca Mountain and so could also result in pressurization of a sealed repository. Eventually the combined effects of both steam production and gas inflow would be expected to produce venting of the repository. We consider these possibilities in somewhat more detail in the following subsections.

Estimates of the Effects of Water and Steam Intrusion

In order to get a rough estimate of what could occur, we can assume that only 10% of the water that was observed to have flowed out at the surface as a consequence of the Borah Peak earthquake in Idaho ($10^8 m^3$ at least) might be expelled by a similar event at Yucca Mountain: that is $10^7 m^3$ of water pumped toward the surface and coming in contact with the repository zone. Then, with the pervasive fracture system existing at Yucca Mountain one could expect about a 20°C drop in rock temperature (to about 100°C) due to transfer of heat to the up-welling water.

The mechanism for heat transfer to the water in such an environment is likely to involve steam production in fractures that are not open to the repository tunnels, but that can be relatively easily opened or extended into the repository by over-pressures produced by the steam inside the fracture. What we have in mind, as the likely mechanical process, is up-welling water occupying void fractures accessible from below followed by vaporization of some of the water producing pressures sufficient to open the fracture and extend it to intersect other fractures. Such fracture growth could allow escape of the vapor into the new conduit region and continued upward flow of the heated water and steam. With upward flow of the vapor and fluid, the pressure would drop in the zone behind the upward moving fluid-gas front and the fracture would tend to close behind the front. However the process would be repeated with the water and steam working its way upward into the repository through the network of largely vertical fractures. The net effect would be a series of mixed steam and hot water "jets" working upward through the fracture zone and eventually into the repository tunnels.

This process would be such that the water must necessarily be in contact with the hot rock in each fracture zone long enough to produce sufficient steam pressure to open the fracture to provide interconnection. Hence it would be a fairly efficient process in terms of extraction of heat from the rock and we expect that, in a rather heavily pre-fractured rock, the mechanism would reduce the temperature of the rock to about the boiling point of water. Since the fractures are open, the initial pressure on the water would be near one atmosphere so that the vaporization temperature would be near 100°C initially. Of course as steam is formed in the fracture, the pressure in the fracture would increase dramatically and raise the vaporization temperature. However, with most of rock at 120°C to 130°C in the repository area, we expect that the pressure would be released by fracture opening well before the vaporization temperature of the water approached the temperatures of the rock. As successive opening and closing of interconnecting segments between fractures occurred we would also expect that opening would become progressively easier. Nevertheless, at some stage the rock temperature would be reduced to the level at which insufficient vaporization would occur to raise the pressure high enough for opening, and the process would stop. We expect, however, that this temperature would not be far above 100°C. Hence an estimate that the rock in the repository area could be reduced by about 20°C, through this "thermal pumping" process, does not seem unreasonable.

The mass of water that could be converted to steam by this process can be roughly estimated by considering the energy balance for the heat exchange between the water, in converting it to steam, and the thermal energy extracted from the heated rock reservoir. That is, the energy balance is given by:

$$M_W^{(v)} (l_w + C_p^{(w)} \Delta T_w) = M_R C_p^{(R)} \Delta T_R$$

where $M_W^{(v)}$ denotes the mass of water vaporized, l_w the latent heat of water (23x10^5

joules/Kgm.), $C_p^{(w)}$ the specific heat of the water (4.2 joules/gm-deg.) and ΔT_w the required increase of water temperature to the boiling point. M_R denotes the mass of rock participating in the heat exchange with an associated temperature decrease of ΔT_R. Here $C_p^{(R)}$ is the specific heat of the rock mass (.83 joule/gm-deg.). The repository volume, that is heated to an average temperature of 120°C, is about 6 x $10^7 m^3$. (The area of the repository is 5.5 km^2 and a depth interval, for such an average temperature, is taken to be 12 meters.) Taking the density of the rock at 2.7 x 10^3 kg/m^3, this gives the mass of heated rock to be 1.8 x 10^{11} kg. If the rock mass is highly permeable, as is the case at Yucca Mountain, then over a reasonable period of time most of the rock mass participates in a heat exchange with the upward moving water, probably in the manner previously described. The estimate of an average temperature drop due to circulation of water into the fractured rock, and heated during the "thermal" pumping described, was around 20°C. That is, $\Delta T_R \approx 20°C$.

In this case the heat exchanged between the thermal reservoir and the water is sufficient to vaporize a mass of water given by

$$M_w^{(v)} = M_R \left[\frac{C_p \Delta T_R}{l_w + C_p^{(w)} \Delta T_w} \right]$$

For water injection at 30° C, then $\Delta T_w = 65°C$ and

$$M_w^{(v)} = 1.2 \times 10^9 \text{kg}.$$

This is about 10^6 m^3 of water vaporized. This corresponds to about 10% of the water assumed to be extruded upward ($10^7 m^3$) and an amount equal to about 1% of the total water extruded at the surface after the Borah Peak earthquake.

Based on the earlier discussion of the thermal pumping mechanism, we can expect that the steam ejected into the repository tunnel system would rapidly raise the internal pressure in the tunnels. The increase in pressure would increase the vaporization temperature for water in the tunnels and at a rather early stage the steam being "pumped" into the repository tunnels would begin to condense into super-heated water. Thus, an equilibrium would be reached by the dynamical process such that the steam pressure in the tunnels would remain at a fixed level and super-heated water would accumulate. Of course as the water came in contact with the waste containers, which would be at temperatures of about 250°C, more steam could be produced and further increase the tunnel pressures. A rough estimate, based on the pressure dependence of the vaporization temperature of water and the efficiency of the additional vaporization of water by the hot cannisters suggests that pressures of a few tens of atmospheres could be reached.

This estimate assumes the tunnels to be closed off to the atmosphere, as is planned for the repository and that there is no natural venting. However, even rather low over-pressures would probably result in natural venting through the fractured rock above the repository, with release of steam into the atmosphere. Therefore it is likely that natural venting will keep tunnel pressures at "modest" levels of, perhaps, several atmospheres, but at the expense of venting steam out of the repository area.

The presence of high temperature water and steam in the repository tunnels and its contact with the waste cannisters presents serious possibilities of very rapid corrosive break-down of the cannisters. While we have only superficially reviewed the literature in this subject area, it is apparent that there are some rather extreme processes which might be expected to occur. One of these involves the production of steam bubbles at the surface of a very hot body. These bubbles are observed to form in such environments and rapidly collapse at short distances from the hot surface, with the production of a high velocity fluid jet directed back toward the surface. The jets produce pitting of the surface and result in greater surface area of hot material exposed to the water. This greater area allows larger numbers of steam bubbles to be formed and an acceleration in the pitting and material break-down. Obviously the process is highly nonlinear and builds upon itself. In the case of hot cannisters, the process could erode the containment vessels and possibly expose waste material to the water and steam environment. The same process could then act to break up the hot nuclear waste and allow it to be rapidly moved into solution or be ejected by steam flows to the surface. Such a possibility underscores the serious consequences that could result from up-welling water intrusion and certainly makes a careful study of the implications of Szymanski's model imperative.

Gas (CO_2) Production and Associated Pressurization Effects

An important additional effect tending to raise the pressure in the repository involves the interpretation that the ground water at depth beneath Yucca Mountain probably contains large concentrations of dissolved CO_2 gas. This gas could be released during the rapid pressure fluctuations in the medium during an earthquake and, as a consequence of upward flow be injected into the repository tunnels along with water and steam.

An aspect of this is discussed in the previous section VII on modeling of the flow effects following an earthquake. One mechanism of gas release and flow was considered in this modeling and demonstrated as being likely to be important in determining the flow associated with seismic pumping. In this process we considered only the equilibrium changes in the stress field produced by an earthquake. The gas coming out of solution was therefore confined to only those zones in which there was a long term (static) drop in the fluid pressure below that prevailing before the earthquake. Nevertheless, the volume of gas released and flowing upward in the fractured medium was found to be appreciable.

However, in addition to seismic pumping of CO_2 and water caused by equilibrium stress changes, there are other mechanisms whereby CO_2 could be released and produce potentially important side effects. In this regard, earthquakes result in spatially complex stress field changes, with locally large transient stress changes which may either increase or decrease the background stress in the medium. That is, as the failure zone expands, at a rate which is somewhat less than the local shear velocity, a nearby material element can experience a rapid increase in the stress levels as the front of the failure zone approaches followed by a rapid decrease as it passes by. If the initial stress state is non-uniform, then the stress levels in the near distance range can oscillate rapidly over several cycles. The magnitude of the effect can be large with ground accelerations well over 1g occurring, as were observed for the San Fernando earthquake.

These large transient changes in the stress levels and their gradients occur near the failure zone during its growth, so that fracture stored fluids would be subjected to rapidly oscillating decompression and compression. This process would be something like shaking a bottle of champagne, with CO_2 rapidly coming out of solution and pressurizing the fractures. Because of the high tectonic stresses, it is likely that fractures would dynamically open and grow as the gas pressure increased. For interconnected fractures, or fractures growing to interconnect, there would be high velocity gas flow carrying liquid along with it and a drop in the gas pressure and water pressure, inducing additional gas outflow from solution. The process could be highly unstable, in that as more fractures were opened by the high transient gas pressure yet more gas would be produced from the more slowly moving fluid as the gas flowed rapidly upward through the fracture system. The amount of CO_2 produced could be large and it could extensively fracture the medium, most likely along rather narrow zones extending upward from the "source areas" near the earthquake failure zone.

In the event of an earthquake near Yucca Mountain, gas dissolution and flows originating from fracture fluid pressure changes due to both long term changes in rock stress and large dynamical stress fluctuations would therefore be expected. Such flows could be expected to inject rather large amounts of CO_2 into the repository tunnels in the right circumstances. for example if an event were initiated at depth along the Stage Coach Road Fault with subsidiary faulting along the north trending faults in the immediate proximity to the proposed repository. The subsequent gas flow would combine with the steam production, and enhance the efficiency of the fracture opening process described earlier, to produce overpressures in repository tunnels. While it is difficult to make predictions with any great degree of confidence because of the many uncertainties in the controlling parameters in the fractured medium affecting access to the repository area, it is not unreasonable to expect a build-up of pressure to as much or more than that expected from steam under conditions prevailing at the site. Thus, in an initially sealed repository one would expect a rapid build-up of steam and heated CO_2 gas to pressures of several tens of atmospheres. Such pressures are more than sufficient to cause venting through the fractured medium above the repository. The consequences for repository safety are similar to those described earlier for steam alone, except with the addition of CO_2 inflow it might be expected that venting would be more energetic and break-down of containment materials more probable and rapid.

IX. Evaluation of the Szymanski CHT Model: September 1990 Consensus Statements of the Entire Panel.

The review panel developed a series of consensus positions on processes, assumptions, and field evidence that are at the core of the conceptual model proposed by Szymanski to explain tectonic effects on the groundwater flow system at and in the vicinity of Yucca Mountain. In this section we summarize the key panel positions as they relate to the Szymanski model. In the Appendix 1 these consensus positions are incorporated in the framework of a statement of the key processes within the Szymanski model in an effort to present them in context. Since these consensus positions, adopted by the full panel as of Sept. 1, 1990, represent the shared views of all the members, they are presented here, in a separate section, to distinguish them from conclusions reached by the present authors that may or may not reflect the current thinking of the other three members of the panel. In any case, the authors of this minority report are in general agreement with the following conclusions and statements; though in some areas we have reached more specific conclusions which are listed in the next section.

1. Geological conditions within the Basin and Range are unusual on a global scale, and highly heterogeneous. It is unclear to what extent Yucca Mountain is representative, unusual or unique within the Basin and Range.

2. The essential feature of the tectonic setting of Yucca Mountain is that it is located in an extensional terrain, in an area with high regional heat flow and nearby evidence of geological-recent volcanic activity, indicating up-welling mantle material.

3. Two models have been proposed by project participants to explain vein and calcrete formation in the vicinity of Yucca Mountain. They differ in mechanism, but the important factor is the indication they provide of the past elevation of the water table at Yucca Mountain.

The JS model, as interpreted by the panel in its position statements on key processes (see the Appendix 1), and based on tectonically-driven up-welling fluids, is considered a valid hypothesis by all panel participants. There was divided opinion on whether the field evidence confirms that the water table has reached the ground surface in the geologically-recent past. The key evidence to consider is the vein and fracture-filling material throughout the saturated zone at Yucca Mountain.

4. The panel considers the issue of saturation of the present unsaturated zone to be the critical issue, rather than the focus on competing hypotheses for origins of the veins and calcretes. For this reason, the panel considered an integrated summary of the hydrogeological history of the unsaturated zone to be a first step and of immediate concern.

5. Because of the extensional tectonic setting, existing and new fractures are opening within the tuffs during the period prior to earthquake rupture. Many fractures will close by strain relief associated with earthquakes. The pattern of strain relief will be complicated and some fractures may be opening or created while others are closing. Open fractures imply that the stress is heterogeneous on a size scale perhaps as large as 10 m, and certainly on a smaller scale. Because the average minimum principal stress is low, as inferred from hydraulic fracturing tests, it is unlikely that the minimum value will be near-zero at many points late in the cycle. The panel does not view the existence of these points of low minimum principal stress as a major driving force, but views them as additional evidence of open fractures that may change aperture with small changes in stress or pore pressure.

6. The lithostratigraphic framework, with its control on the patterns and rates of groundwater flow and the effects of tectonically-induced changes in the hydraulic and transport properties on patterns and rates of groundwater flow, should be viewed as a coupled prob-

lem of mass and energy transport within a deforming fractured medium. This is the case in both the interseismic period, and in the time period following seismic rupture and wall separation. During seismic rupture, large changes in the hydraulic properties of the rock mass are possible.

7. Long-lasting fissures at the ground surface can be related to listric faulting, fluid pressures are involved in the process but only as a second order influence. However, transient pore pressure increases accompanying earthquakes could open veins and joints in the vicinity of the fault. Wall rock separations are not the driving mechanism for resetting of the stress field. Their formation is the result of the kinematics of fault slip, coupled with the listric geometry of faults. The panel considers it probable that large wall rock separations (on the order of several meters) are the results of several to many events.

8. The panel agrees that seismic pumping from dilatant zones at focal depths is not a critical issue since an earthquake, even unaccompanied by seismic pumping, could reset the strain field and close fractures within the tuffs. Of the three panel members expressing an opinion on the likelihood of seismic pumping, estimates of the probability of past and future occurrences of seismic pumping on favorably oriented faults ranged from possible to near certainty.

9. The thermal data characterizing the <u>present-day conditions</u> do not allow for an unequivocal distinction between a convection-dominated system and a thermal regime reflecting regional groundwater flow patterns (an advectively-dominated system). The thermal data do not contradict the view that Yucca Mountain could be late in the tectonic cycle. In view of the magnitude of the regional heat flux, and the nearby presence of recent volcanic activity, the tectonic setting of Yucca Mountain is favorable for hydrothermal con-

lem of mass and energy transport within a deforming fractured medium. This is the case in both the interseismic period, and in the time period following seismic rupture and wall separation. During seismic rupture, large changes in the hydraulic properties of the rock mass are possible.

7. Long-lasting fissures at the ground surface can be related to listric faulting, fluid pressures are involved in the process but only as a second order influence. However, transient pore pressure increases accompanying earthquakes could open veins and joints in the vicinity of the fault. Wall rock separations are not the driving mechanism for resetting of the stress field. Their formation is the result of the kinematics of fault slip, coupled with the listric geometry of faults. The panel considers it probable that large wall rock separations (on the order of several meters) are the results of several to many events.

8. The panel agrees that seismic pumping from dilatant zones at focal depths is not a critical issue since an earthquake, even unaccompanied by seismic pumping, could reset the strain field and close fractures within the tuffs. Of the three panel members expressing an opinion on the likelihood of seismic pumping, estimates of the probability of past and future occurrences of seismic pumping on favorably oriented faults ranged from possible to near certainty.

9. The thermal data characterizing the <u>present-day conditions</u> do not allow for an unequivocal distinction between a convection-dominated system and a thermal regime reflecting regional groundwater flow patterns (an advectively-dominated system). The thermal data do not contradict the view that Yucca Mountain could be late in the tectonic cycle. In view of the magnitude of the regional heat flux, and the nearby presence of recent volcanic activity, the tectonic setting of Yucca Mountain is favorable for hydrothermal con-

vection. A low velocity zone in the crust beneath Yucca Mountain, indicating partial melting or renewed volcanic activity near Yucca Mountain, such as at Crater Flat, would make hydrothermal convection at Yucca Mountain inevitable.

10. The evidence to evaluate past hydrothermal circulation is geologic observation. The quantity of vein filling calcites cannot be explained by seismic pumping. Because of the composition and volume of vein materials at Yucca Mountain, some panel members believe that hydrothermal convection is the only feasible mechanism that explains the origin of vein-filling calcites. The remaining panel members consider it a possibility.

X. Minority Group Evaluation of the Szymanski CHT Model: Conclusions and Recommendations

In addition to the consensus statements of the previous section, with which we subscribe but view as somewhat imprecise general statements, we have arrived, after further investigation, at more definitive conclusions and recommendations that reflect the broader and more detailed study conducted in the last year.

Additional Statements and Conclusions by the Minority Group

The principal additional conclusions relating to the objectives of this study, which is to evaluate the Szymanski CHT model and its relevance to the Yucca Mountain system, are:

- ***The physical and geologic field evidence relating to observed calcretes and calcite-opal veins at the surface and at depth, such as relationships to faulting and hydrothermal alterations, support the interpretation of deposition by up-welling water from considerable depth. This finding is consistent with the Cyclic Hydro-Tectonic model proposed by Szymanski. The geologic observations are not, in several particulars, consistent with a pedogenic, descending water origin for most of these mineral deposits.***

- ***The physical processes and mechanisms incorporated in Szymanski's model for an interactive hydro-tectonic system at Yucca Mountain are meaningful and appear appropriate; and can provide a basis for prediction. The dynamical interactions are, however, highly nonlinear and quantitative predictions based on analytical formulations and numerical modeling are very approximate and incomplete, in that only some of the phenomena inherent in the model can presently be incorporated in a computational program. Nevertheless, in principle Szymanski's model can be described in terms of a set of coupled integral-differential equations that analytically express the dynamics of such a system. In this*** *regard, a preliminary computation, designed to simulate a short time history of seismic pumping in a fractured medium following an earthquake, did predict significant water and gas flows that could be indicative of those to be expected at Yucca Mountain. However, no other quantitative aspects of the model, such as long term convection and chemical deposition, could be evaluated. Nevertheless, while only preliminary, the quantitative analysis so far accomplished does support at least one aspect of the Szymanski model; that is the possibility of pressure driven water and gas flows, from upper to mid-crustal depths, following a large earthquake.*

- *Field observations as well as modeling calculations indicate that gas-assisted (CO_2) flows of high energy may occur in some circumstances. In particular, it is concluded that such flows have occurred at Yucca Mountain in the past and that there is a reasonably high probability that they could also occur in the future. This inference is beyond those drawn by Szymanski and specifically incorporated in his model, but nevertheless is compatible with it.*

- *The isotopic and mineralogic characteristics of the calcite-opal vein deposits at the surface and at depth are similar and imply a common origin of deposition. Owing to sealing and near surface erosional infill, pervasive pedogenic descending-water deposition at depth is highly unlikely. Consequently, the numerous veins at depth are almost certainly due to up-welling water from the Precambrian and the Paleozoic limestone formations beneath Yucca Mountain and, by inference based on isotopic similarity, those exposed at the surface should also have this origin as well.*

- *The isotopic characteristics of the calcite-opal veins at the surface at Yucca Mountain, in particular those at Trench 14, appear to be consistent with up-welling water from depth.*

from 2 to 5 km or deeper, mixed with the shallower water from the tuff formations. If the calcite encrustations on cobbles and soil calcretes used as a pedogenic standard are indeed rain water evaporation deposits, as assumed in the study by Quade and Cerling, then the oxygen-carbon isotopic data for Trench 14 also appears to be consistent with a descending-water "pedogenic" origin. However, if the latter assumption is not true, then a pedogenic model origin is doubtful and deep up-welling water deposition is preferred. If the assumption is true, then both origins can apparently be in agreement with the data and cannot be differentiated on the basis of C-O isotopic data alone.

- *The isotopic characteristics of the vein calcites at Trench 14 appear consistent with a source of deep up-welling water as inferred by Szymanski through his demonstration of the correlation with the water from current "up-welling source regions" in the area of the Nevada Test Site. The lack of correlation between calcite isotopes at Trench 14 and those from the shallow water currently beneath Yucca Mountain, as inferred by Stuckless et. al., can only enforce the conclusion that young meteoric water from shallow depths was not involved, or was only a minor constituent of the water depositing these vein calcites. This conclusion clearly does not negate the possibility of the source being from up-welling water from great depth.*
- *Stuckless et. al. assumed a pedogenic model origin for a number of calcite deposits that they use as a standard. If these are wholly or partly of up-welling origin, then their comparison of these deposits with Trench 14 vein carbonates could force them to a different conclusion; namely that up-welling water from large depths could be responsible for the Trench 14 vein carbonates.*
- *An up-welling, deep source for the water that deposited vein calcites and silica at Yucca*

Mountain is quite possible based on Szymanski's isotope correlations and is permissible on the basis of the Stuckless et. al. study. This possibility is also supported by the inference, by Whelan and Stuckless, of large water table elevation changes at Yucca Mountain in the past; to as much as 500 meters above and 300 meters below the present level.

- *Age dates for the deposition of calcretes and calcite-opal veins at Yucca Mountain are somewhat uncertain, so that a highly confident assessment of when the most recent up-welling has occurred, and how frequently it has occurred in the past, is not possible at present. Indirect lines of evidence and inference lead us to believe, however, that the young ages obtained for some veins and calcretes are probably representative of true depositional ages, but we cannot absolutely rule out different, possibly older, ages.*

- *Based on all lines of assessment, the model proposed by Szymanski appears to be a good working model for interactive dynamical processes at Yucca Mountain, including water flow and mineral deposition, and certainly is not one that can be rejected as incompatible with current observations or theory.* Indeed, it is the only model that is self consistent and compatible with the field observations.

Recommendations by the Minority Group

In addition to recommendations made by the full panel, and included in the Appendix 1, we consider the following to be appropriate and desirable investigations designed to achieve a confident general consensus:

- Age dating of the exposed calcite-opal veins and calcretes, sampled at close intervals spatially, is needed to determine age profiles and times and rates of deposition.
- Trenching, up-slope from Trench 14, is required to determine the source of the slope parallel calcrete deposits at this site. Extending the depth of the present trench to follow the course and extent of the veins with depth is also important.
- Detailed dating, mapping and trenching of some additional fault sites having carbonate deposits is needed to determine the relationship of the carbonate deposits to these faults.
- Seismicity studies and high resolution tomographic studies of the crust and upper mantle in the vicinity of Yucca Mountain would be important in assessing the state and stability of the crust-mantle in this area.
- Complete isotopic characterization and age dating of calcite-opal veins at depth at Yucca Mountain would help confirm their origins. Similarly, sampling of deep waters in boreholes and measurements of isotopic content would be important in comparative studies with vein deposits.
- Comprehensive numerical modeling of the cyclic hydro-tectonic model should be initiated in order to quantitatively assess the character and magnitude of both pressure-driven and thermally-driven flows that might occur in response to large tectonic events under a variety of conditions.

- A complete program of measurements should be initiated in drill holes across the zone of rapid change in the water table level at the north end of Yucca Mountain.

- These or similar projects should be initiated as soon as possible and be planned for completion within two to three years at most. The results should then be integrated with the already extensive data set for this site to assess site suitability. Such an integrated study can best be carried out by a select group of scientists from both inside and outside the official program, but with a majority from outside the project.

XI. General Summary and Overview

In the previous Section X, we have listed our conclusions regarding the scientific merit of Szymanski's hydro-tectonic model and its relevance to the geology and hydrology at Yucca Mountain. These conclusions are supplementary to the consensus statements of the entire panel listed in Section IX and the Appendix 1 of this report and constitute an expansion of the complete panel assessment. These additional conclusions, in part, reflect our later efforts at assessment, since Sept. of 1990, which are summarized in the main part of this minority report.

In this section we wish to address the range of more general issues relating, in part, to how well we can access the suitability of Yucca Mountain as a nuclear waste repository at the present time. This leads us to considerations of uncertainties and ambiguities of interpretation, estimates of confidence in current interpretations and, in the end, to probablistic assessments. As a consequence we are naturally led to think about how to resolve any uncertainties and ambiguities so as to improve our collective confidence in the assessment process.

As is apparent already, and may become more so, we are quite confident in our own assessments of the available field data, the relevance of Szymanski's model and the viability of the Yucca Mountain site as a safe repository for nuclear waste. However, we recognize that our assessments alone are not sufficient to insure a broad range of consensus and appropriate action by the DOE. For these latter events to take place it is evident that a more complete set of data, and integrated analysis of it, is required. As a result, we recommend what we regard as critical field and analysis work that should be pursued immediately in order to resolve remaining issues and allow a broad and confident consensus to be reached within the scientific community and the DOE.

In order to address these goals in the following discussion, we will try to integrate key observations and analysis described in earlier sections to achieve a general overview of the conditions at Yucca Mountain that relate to the containment of nuclear waste. In doing so we will state our conclusions regarding these conditions and also try to address the factors of ambiguity and uncertainty that have caused debate and contention. A principal goal will be to evaluate the ambiguities of interpretation of, certain of the data, but in the broader context of an integrated set of data, in order to either eliminate the uncertainty or at least focus the assessment program on specific new data and analysis that could be obtained to resolve the issue.

On the basis of our evaluation, no other mechanism, other than up-welling ground water from considerable depth, seems entirely capable of explaining the observed calcite-opal vein compositions and the presence of such veins throughout the mountain. In particular, rain deposited calcium carbonate and silica evaporates, which would be confined to the near surface zone by the evaporative process involved in deposition of the minerals, would be extremely unlikely to be able to fill fractures at depth and even at the surface, at the rate and volume required. Nor is rain and infiltrating rain water likely to produce the types of banded calcite and opal veins observed.

The Tuffs along some fault zones in the area, particularly on the south end of Yucca Mountain, are hydrothermally altered indicating that reactive, most likely hot or at least quite warm, water flowed from these fault zones. This can only be explained by upward moving water from depth. These same fault zones are also associated with extensive calcite-opal deposits, both within the fracture zone and immediately down slope along the surface. Some of these surface deposits are very thick, of the order two to three meters. One such calcrete deposit has been dated at 78,000 years before the present. Based on the maximum rate of about 1 meter per million years for rain deposited calcium carbonates at the surface, it is evident that deposition of a thickness of 2-3 meters of such minerals by precipitation - evaporation over about 100,000 years is not credible over such a broad area. Indeed the maximum credible deposition by infiltrating rain water over such a period is deficient by at least an order of magnitude. Consequently, given the thickness, spatial proximity and continuous downslope relationship of the surface calcium carbonate deposits relative to the hydrothermally altered fault zones, it is eminently reasonable to conclude that rapid outflow of heated water, that could only originate from depth, deposited the calcite in the fractured fault zone and down-slope along the surface.

In addition to observations related to calcite veins and surface calcretes, which appear to require up-welling water as the causal mechanism rather than rain water evaporates, data from random sampling of both the surface material and the pore fluids at depth in Yucca Mountain indicate past intrusion of the present unsaturated zone, as well as outflow at the surface, of metal rich fluids. In particular, assays of Yucca Mountain surface vein deposits at Trench 14 and elsewhere by State of Nevada geologists [16-20] show relatively high levels of zinc, lead, molybdenum and other metals compared to background levels. Similarly, recent analysis of pore water, trapped within presently unconnected voids in the Tuff above the water table, show quite high metal content which includes rather high levels of precious metals [21]. This water is likely to be representative of that from the most recent intrusion of water into the unsaturated zone. Since these metals are very unlikely to originate from direct meteoric sources of water, but might very well be expected as constituents in up-welling water from considerable depth, it follows that these observations suggest past invasion of up-welling water into the present unsaturated zone, all the way up to the surface. In view of the young age dates found for some of the calcite veins at depth in the mountain, the last intrusion of metal rich water could have been in the recent past.

Because of the presence of suspended, or "floating" fragments of the local rocks (Tuff) within calcite vein deposits at and near Yucca Mountain, it is also quite likely that in many instances, gas fragmentation processes played an important role in forming the calcite vein deposits. This conclusion is reinforced by the quantitative modeling analysis performed. Therefore, in addition to evidence of hydrothermal alteration along faults, the evidence favoring gas assisted brecciation would also favor a depositional process involving up-welling water and gas from depth and not an evaporative or "pedogenic" processes of deposition. Thus, at an altitude above the planned repository, there is strong evidence for rapid extrusion of calcium - silica rich water and CO_2 gas from depth which appears to have occurred, geologically speaking, in the recent past.

These conclusions, which are in part based on isotope dating of vein and calcrete deposits, are subject to the caveat that the age dates are assumed to represent the time of deposition of the calcites. If this date is in error, in the direction of being much too young, or if the calcretes have been extensively reworked by young meteoric water so as to produce an apparent age that is much younger than the original age of deposition, then we can only say that much of the physical field evidence strongly supports up-welling deposition at some time in the past. The point to be settled is whether these deposits and evidence of hydrothermal activity could date from an much earlier, well documented, volcanic episode that ended some 10 million years ago, rather than the much more recent past. In this case the evidence for up-welling might be interpreted to indicate that a mechanism like that proposed by Szymanski had operated in the relatively remote past, but had become dormant after the end of this major volcanic period, with the rain water reworking only making it appear that outflow at faults and associated calcite deposition occurred recently. This line of argument would also make it possible for a greater period of time to have elapsed between faulting, with associated hydrothermal up-welling, and the accumulation of downslope calcretes. In this case pedogenic processes could, it might be believed, have had the time to slowly accumulate the observed thick downslope calcrete deposits.

In order to address the possibilities that the calcrete age date could be misleadingly young. we have to consider more of the geologic evidence, other than just the near surface data. In particular, we observe that some of the calcite veins intersected at depth by drilling also have very young isotopic ages; several younger than 100,000 years and two as young as 36 ka and 25 ka. We have earlier noted that deposition of such deep veins by evaporation of descending rain water is very unlikely. Likewise, wide-spread reworking of old veins at such depths by the rain water is similarly unlikely, due to inaccessibility because of sealing, infill and near surface evaporation. Therefore, the ages represented in the calcite veins at depth, which span a range similar to those at the surface, are most probably not altered appreciably by reworking. Further, the general isotopic characteristics of the calcite in veins at depth and at the surface are similar. This makes wide-spread reworking at the surface essentially as unlikely as at depth, so that this process is probably not very common at Yucca Mountain.

A remaining possibility is that all the isotopic age measurements are grossly in error, by more than an order of magnitude. Obviously, this is large error and might be viewed as unreasonable purely on the basis of its size. However, it cannot be ruled out at the moment on the basis of our understanding of the intrinsic reliability of the measurement. We merely comment that wide-spread age dating using a variety of methods is critical for a final evaluation.

Nevertheless, in spite of uncertainties in assessing ages of surface vein and calcrete deposits, other results of our assessment lead us to conclusions supporting the model proposed by Szymanski. In particular, our analysis indicates that dilatancy in the local area of Yucca Mountain is likely and furthermore appears to currently manifest itself in the observation of flow characteristics during pumping tests at the site. In addition, the modeling studies incorporating fracture permeability indicate that major pressure-forced flows of water and CO_2 gas are possible after an earthquake in the area, particularly along the Stage Coach Road Fault zone. We also find that the rapid upward migration in the level of the water table to the north and adjacent to Yucca Mountain may also be related to tectonically controlled dilatancy, in that a surface parallel shearing (strike-slip) orientation of the tectonic stresses in this area (as opposed to an extensional orientation at the Yucca Mountain site) would produce much less dilatancy (by an order of magnitude) and consequently a much higher water table.

Our own field studies and assessments of other, independently gathered, field data and subsequent analyses also convince us of the likelyhood of up-welling water in the past; particularly in view of our assessment of the inadequacy of a pedogenic model to explain the calcite veins at depth and many features of the surface exposed veins and calcretes. In this regard, the isotopic characteristics of the calcite veins, while considered by some investigators to support a pedogenic model at Trench 14, appear to us to be, at best, ambiguous and could equally support a model of episodic up-welling involving transport of water and minerals from considerable depth (greater than 2-3 kilometers) to the surface.

Indeed, the recent work by Stuckless *et. al.* [38], even if taken at face value, would simply indicate that the young meteoric water at shallow depths is not isotopically compatible with the vein calcites in Trench 14. A conclusion that this situation is at variance with an origin involving up-welling water, as described by Szymanski, is not appropriate since the CHT model involves transport of water from much deeper than the zone sampled in the latter study. In as much as the isotopic characteristics of the water obviously varies with the type of rock with which the water is in contact and the time of contact, then it is clear that the isotopic "signature" of the water in both the unsaturated and saturated zones will vary with depth and the time of residence. Therefore, young, shallow water would not be expected to have isotopic characteristics matching the vein minerals if the model described by Szymanski applies. Instead, the source water for the calcites would consist of a mixture of shallow and deep waters, and probably have isotopic properties more like the water in the Paleozoics or Precambrian basement rocks. The indications are, in fact, that the isotopic characteristics of the deeper waters more nearly match the vein calcites and calcretes. Therefore, the isotopic data for the vein calcites may well be compatible with the water expected to be involved in up-welling from depth. Indeed, a lack of agreement with young meteoric water seems, if anything, to indicate that the vein calcites may not be isotopically compatible with an infiltrating rain water depositional origin.

Similarly, the isotopic study results reported by Whelan and Stuckless [39] appear ambiguous but could be interpreted to indicate that major changes in the water table from its present level may have taken place in the recent past. Indeed, based on carbon isotope data from calcite veins at depth in the well USW-G4 at Yucca Mountain, the authors state that the data suggest that the water level "may have varied from about 300 meters below to nearly 500 meters above its present position". This, of course, would support a model of episodic up-welling at Yucca Mountain. In particular, Szymanski's predictions of recent and future up-welling are supported if the age dates for the calcite veins represent true ages of deposition for these veins. As noted earlier, we expect that they do, but additional dating using a variety of methods seems to be required for greater confidence.

The study of carbon and oxygen isotopes characterizing the vein calcites at Trench 14 by Quade and Cerling [9] produced a conclusion, by them, that these veins were of pedogenic origin. However, as discussed in this report, Szymanski has argued that these data, as well as the isotopic data used by Stuckless *et al.*, can be equally well fit by an up-welling convective model.

involving transient and spatially variable source and sink flow areas, that is a natural consequence of a CHT model. These two differing conclusions suggest to us that the data are open to various interpretations and that conclusions are also dependent on the initial assumptions which must be made in order to draw any conclusion. In this regard, we note that Quade and Cerling assume that the calcite incrusted pebbles, cobbles and solid calcretes that they use as the standard for pedogenic calcite deposits are in fact deposits from rain water evaporation. However, we have seen several calcrete and calcite incrusted cobble beds at and near the Yucca Mountain area but invariably they have been located down-slope from a fault and, we conclude, are quite probably due to outflow from the fault zone. (See Figure 11 for example.) Therefore, the soil calcretes used by Quade and Cerling could be products of up-welling flows rather than from rain water evaporation. If the cobble incrustations and "soil calcites" are in fact due to deposition from up-welling fluid flows, as they well could be, then their conclusion might have to be that the vein calcites at Trench 14 are compatible with an up-welling water source rather than a rain water derived ("pedogenic") source.

At the least, we view the argument for the origins of the vein calcites based on isotopic characteristics, as put forth to date, to be poorly constrained and, in fact, open to more than one interpretation. Further, the data do not appear incompatible with an up-welling water source of the type discussed by Szymanski, but instead are characterized by a remarkable degree of compatibility.

Taken as a whole, our assessments, particularly those related to observations mentioned earlier in this summary, lead us to believe that a recurrence of up-welling water from depth is possible within a time frame of 10,000 years. In view of the hazard posed by strong upward flooding into a repository, as briefly discussed earlier in this report, it is clear to us that such phenomena, if even remotely likely to reoccur in the next ten thousand years, rules out Yucca Mountain as an appropriate site for high level nuclear waste containment.

In this regard, at the present time if called upon to make a judgement as to the suitability of Yucca Mountain as a site for an underground high level nuclear waste facility, we would not hesitate to reject this site. The probability of water flooding, based on the evidence available, is too high to warrant the risk involved.

However, we have already noted that there is an uncertainty in the ages of deposition of the calcite veins at Yucca Mountain and therefore an uncertainty in how recent, and how frequent, the up-welling has been. Therefore, if the decision is to be put off until more data are available, as will likely be the case, then our recommendation would be to focus subsequent efforts in two or three limited areas to get definitive results and to make a decision very soon, *i.e.* within two to three years.

This accelerated approach appears to us to be warranted in view of the evidence already indicating the extremely strong possibility of up-welling water and gas flows from earthquakes and volcanoes during the Quaternary period (with ages less than about 2 million years). Earthquakes, in particular, are frequent enough and sufficiently predictable (on the time scale involved here) to indicate the probability of recurrences of flooding. What is required here, however, is more confidence in the observations and predictions of water and gas flows connected with large local earthquakes (and volcanoes) and, obviously, more confidence in the age dates of the vein calcites which relate to past water flooding at Yucca Mountain.

Therefore we would recommend, as a minimum, strong efforts in: (1.) Dating calcretes and the minerals in veins at and beneath Yucca Mountain; (2.) Extensive and fundamental modeling studies of induced flow phenomena in fractured media associated with major tectonic events, particularly earthquakes, and (3.) Both detailed mapping and systematic chemical - isotopic studies of calcretes and vein minerals at fault zones at the site, along with isotopic analyses of the water to depths as great as is reasonably possible.

By way of overall summary, we have concluded that Szymanski's model has considerable merit and that it is a good working model for the dynamical processes occurring at Yucca Mountain. We find that the currently available physical evidence for up-welling water and gas flows at Yucca Mountain is certainly strong enough to cause major concerns as to the suitability of the site. However, we have recommended specific areas of study to evaluate remaining uncertainties and to provide the basis for a wider consensus and a confident decision in the near future.

References

(1.) "First Report to the U.S. Congress and the U.S. Secretary of Energy" - Nuclear Waste Technical Review Board, March 1990.

(2.) St. John, C.M. - Thermal Analysis of Spent Fuel Disposal in Vertical Emplacement Borheoles in a Welded Tuff Repository - Sandia Report 84-7207, Nov. 1985.

(3.) O'Neal, M.C., D.W. Gregg, J.N. Hockman, E.W. Russell and W. Stein - Preclosure Analysis of Conceptual Waste Package Designs for a Nuclear Waste Repository in Tuff, Lawrence Livermore National Laboratory Report UCRL, 1986.

(4.) National Research Council "Rethinking High-Level Radioactive Waste Disposal", July 1990.

(5.) Szymanski, J.S. - 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, U S Dept. of Energy Report, Nevada Operations Office, July, 1989.

Szymanski, J.S. - The Yucca Mountain Hydrogenic Deposits - An Engineering Geologist's Inquiry Into Their Genesis and Potential Conceptual Importance, U.S. Dept. of Energy Draft Report, Nevada Operations Office, May, 1990.

Szymanski, J.S. - Comments on the Quade and Cerling Paper, "Stable Isotopic Evidence for a Pedogenic Origin of Carbonates in Trench 14 Near Yucca Mountain, Nevada"; December 1990 Issue of Science: Letter to the Editor of Science Magazine, Jan. 1991.

Szymanski, J.S. - Response to the March 6, 1991 Letter by Cerling and Quade", May, 1991.

Szymanski, J.S. - "Direct Field Observations and Geochemical-Isotopic Evidence for the Conceptual Understanding of the Nevada Test Site Hydrosphere, as Proposed by Szymanski (1989)." Draft Report DOE, April, 1991.

(6.) Healy, J.H., Hickman, S.H., Zoback, M.D., and Ellis, W.L., Report on televiewer log and stress measurements in core hole USW-G1, Nevada Test Site, December 13-22, 1981. U.S. Geological Survey Open-File Report 84-15, 51 pp., 1984.

(7.) Stock, J.M., Healy, J.H., Svitek, J., and Mastin, L., Report on televiewer log and stress measurements in holes USW G-3 and UE-25P#1, Yucca Mountain, Nevada Test Site. U.S. Geological Survey Open-File Report 86-369, 91 pp., 1986.

(8.) Stock, J.M., Healy, J.H. and Hickman, S. H., Report on televiewer log and stress measurements in core hole USW-G2, Nevada Test Site. U.S. Geological Survey Open-File Report 84-172, 48 pp., 1984.

(9.) Quade, J., and T.E. Cerling, Stable Isotopic Evidence for a Pedogenic Origin of Carbonates in Trench 14 Near Yucca Mountain, Nevada. Science, Vol. 250, 1990.

(10.) Machette, M.N. - "Calcic Soils of the Southwestern United States", USGS Special Paper 203, Soils and Quaternary Geology of the Southwestern United States, pp 1-21; 1985.

(11.) Szabo, B.J. and T.K. Kyser - Uranium, Thorium Isotopic Analyses and Uranium-Series Ages of Calcite and Opal, and Stable Isotopic Compositions of Calcite from Drill Cores UE-25a1, USW G-2 and USW G-3/GU3, Yucca Mountain Nevada; USGS-OFR-85-224, 1985.

(12.) Szabo, B.J. and T.K. Kyser - Ages and Stable-Isotopic Compositions of Secondary Calcite and Opal in Drill Cores from Tertiary Volcanic Rocks of the Yucca Mountain Area, Nevada. Geol. Soc. of Am. Bull., V102, 1990.

(13.) Szabo, B.J., W.J. Carr, and W.C. Gottschall, Uranium-Thorium Dating of Quaternary Carbonate Accumulations in the Nevada Test Site Region, Southern Nevada. USGS-OFR-81-119, Open-File Report, USGS, Denver, CO., 1981.

(14.) Whelan, J.F. and J.S. Stuckless - The $\delta^{13}C$ and $\delta^{18}O$ Values of Epigenetic Calcite within Yucca Mountain, Nevada: Paleohydrologic Implications (Abstract) USGS Draft, June, 1991.

(15.) Hay, R.L., R.E. Pexton, T.T. Teague, and T.K. Kyser, Spring-Related Carbonate Rocks, Mg Clays, and Associated Minerals in Pliocene Deposits of the Amargosa Desert, Nevada and California. Geological Society of America Bulletin, 97, 1986.

(16.) Castor, S.B., and J.V Tingley, Mineral Potential Report for the U.S. Department of Energy Administrative Land Withdrawal Application for the Yucca Mountain Addition. 1990.

(17.) Castor, S.B., S.C. Feldman, and J.V. Tingley, Mineral Evolution of the Yucca Mountain Addition, Nye County, Nevada. Report to Science Application International Corporation, 1989.

(18.) Weiss, S.I., D.C. Noble and L.T. Larson - Task 3: Evaluation of Mineral Resource Potential, Caldera Geology and Volcano - Tectonic Framework at and near Yucca Mountain. Report for Oct. 1989 to Sept 1990. Dept of Geol Sciences, Mackay School of Mines, Univ. of Nevada, Reno; 1990.

(19.) Berger, B.R., Geologic-Geochemical Features of Hot-Spring Precious-Metal Deposits. USGS Bulletin 1646, 1985.

(20.) Johnson C. and P. Hummel, "Yucca Mountain Nevada, Nuclear Waste or Resource Rich"; Geotimes, Aug. 1991.

(21.) Smith, M.R. - Natural Radionuclide/Trace Element Hydrochemistry: Characterization of the Yucca Mountain saturated (well waters) and unsaturated (pore waters) zone ground waters, Report to DOE under contract DE-AC06-76RL0-1830, Pacific N.W. Lab. Richland, Washington; May 1991.

(22.) Sibson, R.H., J.M. Moore and A.H. Rankin, Seismic Pumping - a Hydrothermal Fluid Transport Mechanism. *Journal Geol. Soc. London Vol. 131*, pp. 653-659, 1975.

(23.) Wood, S.H. - Regional Increase in Groundwater Discharge After the 1983 Idaho Earthquake: Coseismic Strain Release, Tectonic and Natural Hydraulic Fracturing; from "Proceedings of Workshops XXVIII on the Borah Peak Earthquake", USGS Open-File Report Oct. 1984.

(24.) Wood, S.H. - Observations and Subsequent History of Spectacular Groundwater Flows and Aquifer Pressure Increases: 1983 Borah Peak and 1957 Hebgen Lake Earthquakes, (Abst.) AGU Spring Meeting, May 1991.

(25.) Whitehead, R.L. - "Hydrologic Changes Following the Idaho Borah Peak Earthquakes;" USGS Open - File Report p 83-290, Oct. 1984.

(26.) Swensen, F.A. - Ground-water Phenomena Associated with the Hebgen Lake, Montana, Earthquake of August 17, 1959. USGS Prof. Paper 435, p 159-165; 1964.

(27.) EOS, First Tomographic Study of Western U.S. Completed Transections, American Geophysical Union, Vol. 71, No. 38, 1990.

(28.) Monfort, M.E., and J.R. Evans, Three-Dimensional Modeling of the Nevada Test Site and Vicinity From Teleseismic P-wave Residuals. USGS-OFR-82-409, the USGS, Menlo Park, CA., 1982.

(28.) Torgersen, T., Crustal Fluid Flow: Continuous or Episodic? Report on the AGU Chapman Conference on "Crustal-Scale Fluid Transport: Magnitude and Mechanisms" June 4-8, 1990. EOS, Transactions American Geophysical Union, Vol. 72, No. 3, Jan. 15, 1991.

(30.) McCaig, A.M. - Deep Fluid Circulation in Fault Zones, Geology V. 16, p 867-870, Oct. 1988.

(31.) Durrance, E.M. and M.J. Heath, - Thermal Groundwater Movement and Radionuclide Transport in S.W. England; Mineralogical Magazine, Vol. 49, p. 289-299, April 1985.

(32.) Nesbitt, B.E. and K. Muehlenbachs - Origins and Movement of Fluids During Deformation and Metamorphism in the Canadian Cordillera, Science, Vol. 245, pp. 733-736, Aug. 1989.

(33.) Thorstenson, D.C., E.P. Weeks, H. Hess, and J.C. Woodward, Physical and Chemical Characteristics of Topographically Affected Airflow in an Open Borheole at Yucca Mountain, Nevada. Focus '89 Proceedings: Nuclear Waste in the Unsaturated Zone, 1989.

(34.) Fyfe, W.S., N.J. Price and A.B. Thompson, *Fluids in the Earth's Crust*, Elsevier Sc. Publ. Co., 1978.

(35.) Price, N.J. and J.W. Cosgrove, *Analysis of Geologic Structures*, Cambridge Univ. Press, 1990.

(36.) Stuckless, J.S., Presentation to the NRC, Unpublished, 1990.

(37.) Frazier, G.A., Hydrogenic Veins in Sand Ramps at Busted Butte, DOE Memorandum, SAIC, April 1991.

(38.) Stuckless, J.S., Z.E. Peterman, D.R. Muhs, U and Sr Isotopes in Ground Water and Calcite, Yucca Mountain Nevada: Evidence Against Up-welling Water, in Science, Oct. 25, 1991.

(39.) Bish, D.L., Revised Mineralogical Summary for Yucca mountain, Los Alamos Laboratory Technical Report, 1989.

(40.) Livingston, D., Transmittal of Draft Critique of "An Evaluation of Evidence Pertaining to the Origin of Vein Deposits in Trench 14, Nevada Test Site, Nevada", by J. S. Stuckless, Feb. 1991.

(41.) Reheis, M., Soil Pits at Fortymile Wash, "DDE-YMP Field Trip to Yucca Mountain and the Surrounding Region" for the National Academy of Sciences Panel on Coupled Processes, Oct. 18-20, 1990.

(42.) Cerling, T.E. and J. Quade, Letter to C. Gilbert, Letters Editor: Science Magazine, March 6, 1991.

(43.) Archambeau, C.B., E.A. Flinn, and D. G. Lambert, Fine Structure of the Upper Mantle, Journal of Geophys. Research, vol. 74, 1969.

(44.) Archambeau, C.B. and C. Sammis, Seismic Radiation from Explosions in Prestressed Media and the measurement of Tectonic Strain in the Earth, Rev. of Geophysics and Space Physics, vol. 8, No. 3, Aug. 1970.

(45.) Schlesinger, "The Formation of Caliche of Soils of the Mohave Desert, California", Geochemica et Cosmochimica Acta, Vol. 49, Permagon Press, pp. 57-66, 1985.

Appendix 1

A Consensus Statement of the Review Panel Evaluation of Key Physical Processes in the Szymanski Model and Recommendations for Additional Investigative Studies (Sept. 1, 1990)

Appendix 1

A Consensus Statement of the Review Panel Evaluation of Key Physical Processes in the Szymanski Model and Recommendations for Additional Investigative Studies (Sept. 1, 1990)

In an attempt to comprehend the many processes in the JS model, and the linkage between these processes, the panel found it helpful to construct a "table" that summarizes the key components of the JS model. † This table is reproduced here. It is based on the identification of seven key processes. For each process the panel identified the consequences of that process (that is, why the process is included in the JS 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, reflect the author's (J. Szymanski) viewpoint. In panel discussions the author 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 draft of the table were added if the author felt important points had been omitted. New evidence not included in the author's 1989 report, but which the author feels support his model, is included in the table and is so identified. *(Other data and evidence, added in various reports by the author after Sept. 1990, are not considered here but have been referred to and discussed in the body of this minority panel report.)*

For each key process the panel attempted to reach a series of consensus positions. These consensus positions reflect the panels assessment of the process, its consequences and the evidence to support its occurrence. For each process the panel developed a series

† The abbreviation "JS model" used throughout this appendix refers to J.S. Szymanski's hydro-tectonic model of the Yucca Mountain area as described in his report of 1989.

of recommendations for data collection and/or analysis that, if implemented, could contribute to a better understanding of the potential influence of the tectonic setting on the hydrologic system at Yucca Mountain. Within this table no priority is assigned to the recommendations; for reasons of clarity they are ordered according to process. In the next section of the report these recommendations are reproduced as a prioritized list.

The seven key processes in the JS model have been identified as:

(1) Mantle Convection

(2) Cyclic Variation in the In-Situ Stress Field

(3) Tectonic Deformation Model: The surface Z(x,y,t) (Depth range of Open Fractures) and It's 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 (2) through (6) are closely related, and represent a finer subdivision of the JS hypothesis than is implied in Processes (1) and (7).

Process 1. Mantle Convection

Consequences:

(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 (JS):

- Seismic velocity anomaly in the upper mantle, suggesting a partially molten upper mantle.

- Scale of the inhomogeneity in P wave seismic velocities, reflecting heterogeneous viscosity.

- Volcanic cones, with a basaltic composition.

Panel Position

Inferences based on mantle convection are not a critical aspect of the proposed model. The essential feature is that Yucca Mountain is located in an extensional terrain with regional high heat flow and nearby evidence of geologically recent volcanic activity indicating upwelling mantle material. Doming of the crust due to upwelling in the mantle is the likely cause of extension; a model of basal shear beneath the low velocity zone is not needed.

Geological conditions within the Basin and Range are unusual on a global scale, and highly heterogeneous. It is unclear to what extent Yucca Mountain is representative, unusual or unique within the Basin and Range. A characteristic length scale of heterogeneities may be on the order of 50 to 100 km, based on inferences from geological data.

Recommendations:

(1) High-resolution seismic tomography, to examine the possibility of low-velocity zones in the crust in the vicinity of Yucca Mountain, should be initiated and could

indicate the presence of partial melt. This data could be used to evaluate the potential for increasing heat flow through time in the vicinity of Yucca Mountain. This recommendation supports refinement of earlier work by Montfort and Evans (1982).

Process 2. Cyclic Variation in the In Situ Stress Field

"Cyclic", as used here, means a sequence of processes develop through time which is re-initiated following a major earthquake on one of the faults in the area. Cyclicity does not imply periodicity.

Consequences:

(i) The rock mass at Yucca Mountain must be characterized in terms of the cyclic deformation of a fractured medium. Fractures within the medium are pervasive. Dilated fractures reflect those with a preferential orientation to the stress field at a given point in space and time.

(ii) Deformation is cyclic because of renewed faulting (large scale failure). Deformation is variable in space because of local stress domains, each associated with slip on a major fault having a characteristic length of the order of 5 - 10 km. Local stress domains are distinguished on the basis of their position in the time cycle. The time scale of cyclicity is on the order of 10^4 years.

Evidence (JS):

- The state of stress across Yucca Mountain, and comparisons to other areas on the NTS.
- Inferences of the state of stress from hydraulic tests, and 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 250,000 years (the latter estimate using veins in alluvium).

Panel Position

Because of the extensional tectonic setting, existing and new fractures are opening within the tuffs during the period prior to earthquake rupture. Open fractures will probably be more frequent in the welded tuffs than in the nonwelded tuff units. Many fractures will close by strain relief associated with earthquakes. The pattern of strain relief will be complicated and some fractures may be opening or created, while others are closing.

While the concept of strain domains (of order 10 to 100 Km^2) is useful, it will be difficult, if not impossible, to define their boundaries in an operational sense.

Open fractures imply that the stress is heterogeneous on a size scale perhaps as large as 10 m, and certainly on a smaller scale. Because the average minimum principal stress is low, as inferred from hydraulic fracturing tests, it is unlikely that the minimum value will be near-zero at many points late in the cycle. The panel does not view the existence of these points of low minimum principal stress as a major driving force, but views them as additional evidence of open fractures that may change aperture with small changes in stress or pore pressure. Because of standard procedures in carrying out hydraulic fracturing and slug tests, these tests measure stress (or allow inferences on stress) on different size scales, and in intervals with different fracture characteristics.

Because seismic data can be used to infer oblique movement on faults, one may infer that it is probable that the axis of maximum principal stress is far from vertical, except near the ground surface. Consequently, deformation may involve a significant component other than extension and these should be resolved or investigated by surface and bore-hole strain measurements.

Recommendations:

(1) Establishment of a surface strain monitoring network, and installation of at least one borehole strain meter is recommended. The borehole data should be collected in a way that permits correlation of strain measurements with fluid pressure fluctuations.

(2) A program of distributed in-situ stress measurements in existing boreholes, with emphasis on measurements in boreholes located downgradient, across, and upgradient of the region at Yucca Mountain with the steep slope on the water table is appropriate. The full length of each borehole should be examined to identify suitable locations for in-situ stress measurements by hydraulic fracturing. Hydraulic slug tests may also be designed to provide estimates of in-situ stress. Any program of in-situ stress measurements and permeability measurements (recommended later) should be planned as conjunctive experiments and interpreted jointly.

(3) An investigation of possible oscillations of water level in continuously monitored boreholes should be implemented to: (a) better resolve the character and origin of anomalous water level data, and (b) determine water table changes and infer the response of the fractured tuffs to seismic loading. The sampling rate of fluid pressure measurements should be on the order of a few measurements per second. Open hole pressure changes in response to seismic loading should be monitored in 5 to 10 boreholes, with the presure response in short, packed-off intervals below the water table

monitored in at least 3 boreholes.

Process 3. The Tectonic Deformation Model and Its Influence on Field Scale Hydraulic Properties of the Tuffs

Consequences:

(i) Tectonically-controlled groundwater flow system in the tuffs.

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

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

Evidence (JS):

- The present water table configuration and its correlation with the 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 and temporal variations in water levels in the limited data record that is available.

Panel Position:

The lithostratigraphic framework, with its control on the patterns and rates of groundwater flow, and the effects of tectonically-induced changes in the hydraulic and transport properties on patterns and rates of groundwater flow should be viewed as a coupled problem involving mass and energy transport within a deforming fractured medium. This is the case in both the interseismic period and in the time period following seismic rupture and wall rock separation. During seismic rupture large changes in the hydraulic properties of the rock mass are possible.

According to JS, 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 it the magnitudes of these stress fluctuations 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. Although this is a useful concept, the depthward motion of this surface during the interseismic period, as proposed by JS, would be difficult to verify.

Closure of fractures will decrease the bulk hydraulic conductivity of the tuffs. However, as noted in Process 2, the pattern of strain alteration will be complex, some fractures can be expected to open and, in addition, the closure of unmated fractures is difficult. Therefore, the magnitude of the effect on hydraulic conductivity is uncertain. Additional decreases in hydraulic conductivity can result from sealing of fractures due to precipitation of calcium, silica, etc. from upwelling fluids driven by hydrothermal convection (see Processes 6 and 7).

Recommendations:

(1) Implementation of a comprehensive field program to determine the factors giving

rise to the steep water table gradient at Yucca Mountain is recommended.

(2) A program of hydraulic tests to characterize the permeability of the rock mass below the water table at Yucca Mountain, and to determine its variation with lithology and structure, would be desirable. Small packer intervals should be used. These tests should be coordinated with the study of stress values in the various regions near and within the area of the steep water table gradient at the north end of Yucca Mountain (see Process 2).

Process 4. Episodic Wall Rock Separation of Large Magnitude

Consequences:

(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. Limit equilibrium conditions only occur close to the ground surface following stress release.

(ii) Formation of wall rock separations on fissures, and formation of breccias.

(iii) Change in medium conditions that enhance hydrothermal convection.

Evidence (JS):

- Field observations (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.

Panel Position:

Long-lasting fissures at the ground surface can be related to listric faulting, fluid pressures are involved in the process but only as a second order influence. However, transient pore pressure increases accompanying earthquakes could open veins and joints in the vicinity of the fault.

Wall rock separations are not the driving mechanism for resetting of the stress field. Their formation is the result of the knematics of fault slip, coupled with the listric geometry of faults. The panel considers it probable that large wall rock separations (on the order of several meters) are the result of several to many events.

The implosion process associated with fault opening is another potential mechanism for creating breccias.

Recommendations:

(1.) A study to determine to what extent wall rock separations are a characteristic feature of fault zones within the Basin and Range could be helpful. The question to be addressed would be: Is such opening unique to the region around Yucca Mountain?

Process 5. Dilatant Zones At Focal Depths - Seismic Pumping

Consequences:

(i) A condition leading to wall rock separation upon failure.

(ii) A condition allowing fluid flow to the fault zone and the region surrounding a fault.

These are two consequences stated in the 1989 report. In discussions with the panel, JS acknowledges that seismic pumping from a dilatant zone at focal depths is not an essential part of the model; other processes could trigger the readjustment of the hydrological system. JS emphasizes that the key issue is that the critical value of closure pressure ($\bar{\sigma}_c$)

approaches zero. However, JS is "absolutely sure" on the basis of field evidence that seismic pumping has occurred at Yucca Mountain. Seismic pumping does not, however, necessarily contribute to vein formation.

Evidence (JS):

- Analogy to groundwater discharges related to seismic events in other tectonically active settings.

- Field evidence, ie. wall rock separations and some breccias indicate a pressure pulse at some time in the past.

- The overall tectonic setting.

Panel Position:

The panel agrees that seismic pumping from dilatant zones at focal depths is not a critical issue since an earthquake, even unaccompanied by seismic pumping, could reset the stain field and close fractures above the surface Z. Those members expressing an opinion felt that seismic pumping at Yucca Mountain was a possibility for favorably-oriented faults. (Two members felt unable to judge the issue. Of those expressing opinions, the probability of past and future occurrences of seismic pumping ranged from possible to near certainty.)

Recommendations:

(1) Stress measurements and surface strain measurements are essential to evaluate the probability of a large (M=7) earthquake, within the time frame of interest, on faults such as the Stage Coach Road Fault that may be favorably oriented for seismic pumping. Such measurements are therefore, recommended.

Process 6. Vein-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 that the water table has reached the ground surface in the past.

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

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

Evidence (JS):

- Surface textures, banding , frequency of veining, morphology and structural relationships within veins, between veins and calcretes.

- Elimination of other possible origins (ie., rainfall, followed by surface and/or shallow subsurface flow)

- Isotopic characteristics and precipitation temperature of deposits classified as travertines by Szebo and Kyser (1984).

Additional evidence has been given to the panel that does not appear in the 1989 report:

- Inferred precipitation rates of minerals (fast).

- Uranium series geochemistry (low values and heterogeneous).

- Correlation of oxygen/carbon ratios with those in the Amaragosa Desert.

- Depthward gradient in $\delta_{18}O$, $\delta_{13}C$, implying a geothermal gradient greater than 22°C/km.

Panel Position:

Two models have been proposed by project participants to explain vein and calcrete formation. They differ in mechanism, but the important factor is the indication they provide of the past elevation of the water table at Yucca Mountain. The JS model, as interpreted by the panel in its position statements on key processes (which is based on tectonically-driven upwelling fluids) is considered a valid hypothesis by all panel participants. There was divided opinion on whether the field evidence confirms that the water table has reached the ground surface in the geologically-recent past. The key evidence to consider is the vein and fracture-filling material throughout the unsaturated zone at Yucca Mountain.

The panel has examined an interpretation of geochemical data provided by JS, and also various reports by project investigators and other scientists. Differing weight was given by the panel members to inferences drawn for the geochemical data. The panel agreed that the role of the available geochemical data in evaluating the JS model is limited because the processes envisioned in the formation of the veins and calcretes permit different fluid pathways that are difficult to distinguish on the basis of the existing geochemical data. Thus, the available geochemical data cannot rule the JS model out.

The panel considers the issue of saturation of the present unsaturated zone to be the critical issue, rather than the focus on competing hypotheses. For this reason, the panel considers an integrated summary of the hydrogeological history of the unsaturated zone to be a first step and of immediate concern.

Recommendations:

(1) An integration of information on vein/fracture filling, character, relative abundance with depth, volume, chemistry, age, and other mineralogical information bearing on hydrogeological history of the unsaturated zone at Yucca Mountain is considered critical and strongly recommended. Analysis of age and spatial relationships must be included.

(2) Based on integrated information, further analyze the age, chemistry, temperature of formation and other data in order to examine the merits of upwelling fluids or other mechanisms to form veins within the unsaturated zone.

(3) Extend the exploration of Trench 14 across the ridge and to depth to identify the source of fluids for surface deposits at Trench 14.

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, silica, and uranium to the surface to produce veins and calcretes.

(iii) Healing of the rock mass adjacent to the fault zone by cementation, for a distance on the order of 1 km around 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 by transport, resulting in a temperature increase in the upper crust, beginning after seismic rupture, on a time scale of order 10^3 year.

Evidence (JS):

- Occurrence of spring deposits at elevations far above the present water table

- Isotopic signatures, age dates of deposits.

- Present-day thermal gradient, compared to paleotemperatures inferred from precipitation temperatures of calcites.

- Expected Rayleigh numbers exceed critical Rayleigh numbers (based on assumed geometry, permeability, geothermal gradient).

- Surprisingly large lateral temperature gradients at and immediately below the water table.

- Laterally-heterogeneous heat input from the mantle.

- Identification of water table mounds at several sites within the NTS.

Panel Position:

The thermal model presented by JS is consistent with his interpretation of veins and calcretes as resulting from upwelling fluids. The thermal data characterizing the present-day conditions do not allow for an unequivocal distinction between a convection-dominated system and thermal regime reflecting regional groundwater flow patterns (an advectively-dominated system). The thermal data do not contradict the view that Yucca Mountain could be late in the tectonic cycle. In view of the magnitude of the regional heat flux, and the nearby presence of recent volcanic activity, the tectonic setting of Yucca Mountain is favorable for hydrothermal convection. A low velocity zone in the crust beneath Yucca Mountain, indicating partial melting (see recommendation to evaluate this possibility under Process 1), or renewed volcanic activity near Yucca Mountain, such as at Crater Flat, would make hydrothermal convection at Yucca Mountain inevitable.

The evidence to evaluate past hydrothermal circulation is geologic observation. The quantity of vein filling calcites cannot be explained by seismic pumping. Because of the composition and volume of vein materials at Yucca Mountain, some panel members believe that hydrothermal convection is the only feasible mechanism that explains the origin of vein-filling calcites. The remaining panel members consider it a possibility (see Process 6).

Recommendations:

(1) A quantitative basis for establishing the sequence of hydrothermal events, and the magnitude of their impact on the chemical and hydrologic system, needs to be developed. In particular, the potential magnitude of a water table rise due to hydrothermal convection should be evaluated, together with the interaction of advective heat transfer and hydrothermally-driven convection, given the permissible range of parameter values and timing of basal boundary fluxes. These model studies should focus on the geologic setting at Yucca Mountain.

(2) Dedicated boreholes, designed specifically to obtain reliable subsurface temperature measurements, undisturbed by fluid flow along the axis of the borehole, are recommended in order to better define the thermal regime at Yucca Mountain.

SUMMARY OF RECOMMENDATIONS

Panel recommendations are grouped into three categories:

A. Recommendations the panel assigns high priority.

B. Recommendations that relate to issues the panel views as important to resolve.

C. Recommendations that relate to a longer-term improvement in the understanding of how the tectonic setting at Yucca Mountain may influence the hydrologic system.

Priority A: Recommendations that the Panel Assigns High Priority

(1) Integrate information on vein/fracture filling, character, relative abundance with depth, volume, chemistry, age and other mineralogical information bearing on the hydro-geological history of the unsaturated zone at Yucca Mountain. Analysis of age and spatial relationships must be included.

(2) Based on integrated information, further analyze the age, chemistry, temperature of formation and other data, to examine the merits of upwelling fluids or other mechanisms to form veins within the unsaturated zone.

(3) Extend the exploration of Trench 14 across the ridge and to depth to identify the source of fluids for surface deposits at Trench 14.

(4) Implementation of a comprehensive field program to determine the factors giving rise to the steep water table gradient at Yucca Mountain.

Priority B: Recommendations That Relate to Issues the Panel Views as Important to Resolve

1. Establishment of a surface strain monitoring network, and installation of at least one borehole strain meter. The borehole data should be collected in a way that permits

correlation of strain measurements with fluid pressure fluctuations.

2. A program of distributed in-situ stress measurements in existing boreholes at Yucca Mountain, with emphasis on measurements in boreholes located downgradient, across, and upgradient of the region having a steep slope of the water table surface. The full length of each borehole should be examined to identify suitable locations for in-situ stress measurements by hydraulic fracturing. Hydraulic slug tests may also be designed to provide estimates of in-situ stress. Any program of in-situ stress measurements and permeability measurements (recommended later) should be planned as conjunctive experiments and interpreted jointly.

3. An investigation of possible oscillations of water levels in continuously monitored boreholes should be implemented to: (a) better resolve the character and origin of anomalous water level data, and (b) determine water table changes and infer the response of the fractured tuffs to seismic loading. The sampling rate of fluid pressure measurements should be on the order of a few measurements per second. Open hole pressure changes in response to seismic loading should be monitored in 5 to 10 boreholes, with the pressure response in short, packed off intervals below the water table monitored in at least 3 boreholes.

4. A program of hydraulic tests should be initiated to characterize the permeability of the rock mass below the water table at Yucca Mountain and to determine its variation with lithology and structure. Small packer intervals should be used. These tests should be coordinated with the study of stress values in the various regions near and within the area of the steep water table gradient (see Process 2).

5. A quantitative basis for establishing the sequence of hydrothermal events, and the

magnitude of their impact on the chemical and hydrologic system, needs to be developed. In particular, the potential magnitude of a water table rise due to hydrothermal convection should be evaluated, together with the interaction of advective heat transfer and hydrothermally-driven convection, using the permissible range of parameter values and timing of basal boundary fluxes. These model studies should focus on the geologic setting at Yucca Mountain.

Priority C:Recommendations that Relate to a Longer-Term Improvement in the Understanding of How the Tectonic Setting at Yucca Mountain May Influence the Hydrologic System

(1.) High-resolution seismic tomography, to examine the possibility of low-velocity zones in the crust in the vicinity of Yucca Mountain indicating the presence of partial melt, should be initiated. This data could be used to evaluate the potential for increasing heat flow with time in the vicinity of Yucca Mountain. This recommendation supports refinement of earlier work by Montfort and Evans (1982).

(2.) A study to determine to what extent wall rock separations are characteristic feature of fault zones within the Basin and Range; in particular is such opening unique to the region around Yucca Mountain?

(3.) Stress measurements and surface strain measurements are essential to evaluate the probability of a large (M=7) earthquake, within the time frame of interest, on faults such as the Stage Coach Road Fault that may be favorably oriented for seismic pumping.

(4.) Dedicated boreholes designed specifically to obtain reliable subsurface temperature measurements, undisturbed by fluid flow along the axis of the borehole, should be installed.