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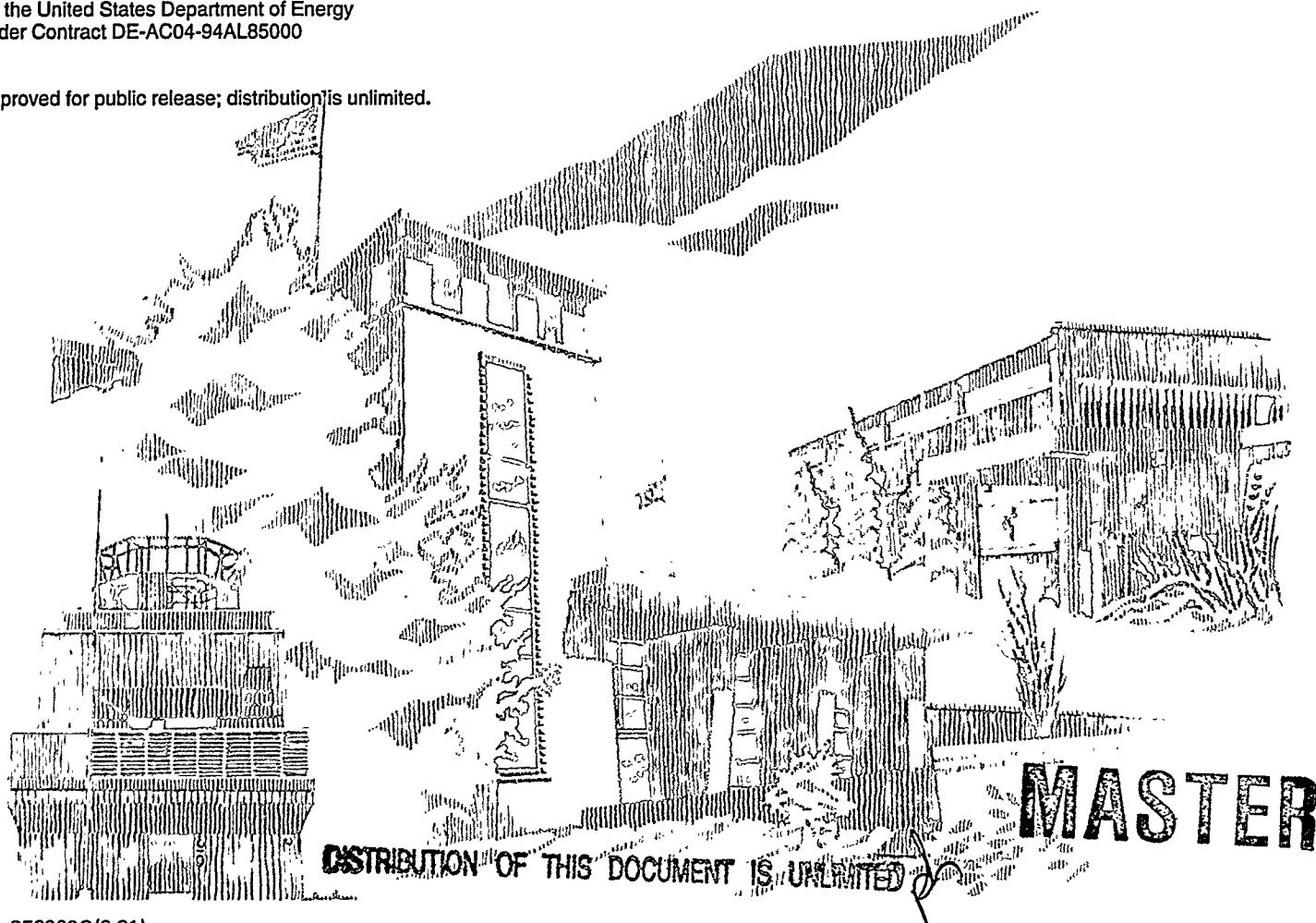
Yucca Mountain Site Characterization Project

Scenarios Constructed for the Effects of the Tectonic Processes on the Potential Nuclear Waste Repository at Yucca Mountain

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Prepared by
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for the United States Department of Energy
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SCENARIOS CONSTRUCTED FOR THE EFFECTS OF TECTONIC PROCESSES ON THE POTENTIAL NUCLEAR WASTE REPOSITORY AT YUCCA MOUNTAIN

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Abstract

A comprehensive collection of scenarios is presented that connect initiating tectonic events with radionuclide releases by logical and physically possible combinations or sequences of features, events and processes. The initiating tectonic events include both discrete faulting and distributed rock deformation developed through the repository and adjacent to it, as well as earthquake-induced ground motion and changes in tectonic stress at the site. The effects of these tectonic events include impacts on the engineered-barrier system, such as container rupture and failure of repository tunnels. These effects also include a wide range of hydrologic effects such as changes in pathways and flow rates in the unsaturated and saturated zones, changes in the water-table configuration, and in the development of perched-water systems. These scenarios are intended to guide performance-assessment analyses and to assist principal investigators in how essential field, laboratory, and calculational studies are used. This suite of scenarios will help ensure that all important aspects of the system disturbance related to a tectonic scenario are captured in numerical analyses. It also provides a record of all options considered by project analysts to provide documentation required for licensing agreement. The final portion of this report discusses issues remaining to be addressed with respect to tectonic activity.

ACKNOWLEDGMENTS

Isaac Block prepared figures and sketches for this report. Dominic Martinez assisted us with several sketches. We are grateful for their support.

This report was prepared under the Yucca Mountain Site Characterization Project WBS number 1.2.5.4.1, QA Grading Report # 1.2.5.4.1. The planning document that guided this work activity was WA-0036. The information and data documented in this report are not qualified and will not be used in licensing the repository.

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

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1.0 INTRODUCTION

This report identifies possible tectonic events and processes associated with tectonic activity that could lead to future release of radionuclides from the potential Yucca Mountain high-level waste repository site. The performance-assessment method detailed in the Site Characterization Plan (DOE, 1988) requires that a set of scenarios encompassing all significant radionuclide release paths to the accessible environment be described. This report attempts to catalog the details disruptions caused by tectonic activity presumed to aid release of radionuclides.

To organize the information obtained from many sources, we chose a logical structure called a generalized event tree. The event tree is used to systematically organize features, events and processes (FEPs) and the understanding that investigators have of these phenomena. The event tree is called generalized because its components include features and processes, as well as events. The event tree is then used as a tool for systematic construction of scenarios. A "scenario" is defined here to be a single connected, continuous path through the tree, from the initiating event and continuing down to the release, with the requirement that the component elements in the path are well-enough defined so that a well-posed, calculable problem results. To clarify some of the component elements, a series of sketches supplements the verbal description; each scenario is defined by a path and its associated sketches. Segments of the tree showing one or more paths will be discussed in detail until the tree is completely described. The important issues of exclusivity and competing processes are not addressed by this definition of scenario. These issues will be addressed at some later date when work of principal investigators (PIs) has added enough information that the number of scenarios has been reduced.

Construction of a complete and exhaustive catalog of release scenarios requires a synthesis of all currently available information concerning both the natural and engineered system components. Completeness in the sense of inclusion of all possible FEPs and development of all possible scenarios, is not possible; however, we do attempt to include all the physical principles and information known to us that we presume to have potential to contribute to significant radionuclide release. We will explore additional release scenarios should they become of concern.

Identification of a scenario presumes no knowledge of its probability of occurrence; rather a scenario represents a description of physically possible connected FEPs leading to a possible release of radionuclides to the accessible environment. Elimination of FEPs of little consequence, FEPs of very low probability of occurrence, and those that are, contrary to our current assumptions, physically impossible, will be based on observations,

calculations and experiments. We assume that the vast majority of these scenarios will eventually be eliminated, but by describing every scenario considered, the reader is allowed to judge independently whether the work is complete and whether any scenario should be omitted in later stages of analysis. We expect to revise these scenarios if principal investigators suggest revisions and omissions of both scenarios and FEPs.

In particular, there seem to be four opportune times for such reexamination and revision: when site characterization information from surface-based testing is completed, when entrance to the underground workings is possible and incorrect presumptions about behavior of the potential site can be corrected, when the Safety Analysis Report is required, and finally, at decommissioning, when 30 to 50 years of operational experience have been accumulated.

Although there are many definitions of "scenario," the one used here requires sufficient detail that, if an alternative definition is required for any purpose, these results can be restructured in the required form. In addition, this definition parallels how workers lay out their experimental or calculational plans, so communication is relatively easy and PIs have little difficulty discovering our errors, omissions or misinterpretations of their data or results. Scenario development is an iterative process that depends on feedback from PIs.

1.1 Methodology for Incorporating Scenarios into Future TSPA Analyses

Scenario development is a critical first step in TSPA analyses. A formalized approach to TSPA analyses includes the following activities: 1) scenario construction and screening, 2) assignment of probabilities to FEPs, 3) development and implementation of conceptual models to describe FEPs, 4) development of parameter distributions for the models, 5) calculations and simulations of FEPs described by models, and 6) evaluation of the results against the performance measures. The methodology is iterative; at any stage, the results may be used to modify prior steps. Completion of the first two steps in the six-step methodology are necessary to incorporate scenarios into a TSPA analysis.

This report expands on prior seismic-scenario development done by Barr and others. Analyses of several individual FEPs related to direct seismic effects mentioned in this work have already been published. These include the effects of rock fall on waste-package performance due to direct damage (Gauthier and others, 1995), and changes in water-table elevation in response to seismic events (e.g., seismic pumping)(Arnold, 1996).

The current report is a comprehensive list of scenarios showing how tectonic events may alter the modes of release from a potential repository at the Yucca Mountain site. This list is accompanied by a short list of open issues that may expand or contract the scenarios of interest, as they are resolved. The current work subsumes the prior scenario-development work, and it also includes the results of USGS field studies and other analyses. In addition, there has been interactions with other participants to guide Project scientific programs.

To incorporate seismic effects into the next TSPA analyses, the scenarios list from this work will first be sorted to identify scenarios that address the consequences of fault movement through the potential repository. Additionally, those scenarios that describe fault movement outside the potential repository will be cataloged. The ranking process will involve examination of the potential consequences of individual FEPs and their context. The examinations will produce: a) the most likely scenarios, based on current interpretation of behavior, and b) the most important scenarios, based on the estimated impacts on TSPA performance measures (such as dose, or release). Additional scenario screening will be done when the DOE's Seismic Effects Topical Report (due in early 1997) becomes available. In many cases, scenarios cannot be adequately prioritized without additional data or analyses. As pertinent site data or analyses become available, they will be used to continue the screening process.

Having identified a broad list of scenarios and ranked their significance, the next step is to have experts in the fields of seismic effects, seismology, and geohydrological processes review and evaluate the scenarios. The Electric Power Research Institute (EPRI) has done a preliminary probabilistic seismic hazard assessment using expert elicitation, and that work will be used as part of the basis for development of scenario probabilities. Project planning for 1997 and beyond includes several activities to do scenario development for the TSPA-VA. The TSPA-VA scenarios activities follow the methodology described here.

2.0 BASIS

A number of concerns must be addressed in the scenarios constructed here:

GEOLOGIC CONSIDERATIONS

I. Location of tectonic event

A. Proximal:

1. within the repository
2. adjacent to repository

B. Distal/regional

II. Nature of tectonic event/geologic effect at site

A. Discrete deformation (fault offset through repository)

1. new fault forms
2. new strand forms on old fault
3. existing fault strand reactivated

- B. Distributed deformation in repository
 - 1. fracturing/brecciation
 - 2. (brittle) bending
 - 3. uplift/subsidence
- C. Ground motion
- D. Change in stress state

III. Large-scale fault geometry

- A. Deeply penetrating faults
- B. Surface faults, listric into shallow detachment

ENGINEERING CONSIDERATIONS

IV. Effects on engineered-barrier system

- A. Waste package rupture
- B. Tunnel failure/rock fall
- C. Hot repository
- D. Cold repository

HYDROLOGIC CONSIDERATIONS

V. Effects on rock properties

- A. Volumetric rock strain(porosity increase/decrease)
 - 1. porosity change with little or no permeability change
 - 2. porosity change with permeability change
- B. Strain-induced permeability change
 - 1. within/adjacent to fault zone
 - a. k (permeability) change along fault
 - b. k change across fault
 - 2. widespread K change (not limited to at/near one fault)

VI. Hydrologic process changes

- A. UZ (unsaturated zone) tectonic effects at/near/through repository
 - 1. Change in volume of flow
 - 2. Change in flow velocity/pathway
 - 3. Development of perched horizon/perched flow
- B. SZ (saturated zone) tectonic effects
 - 1. Change in water-table elevation/configuration
 - 2. Change in flow pathway/velocity
 - a. Within tuff aquifer
 - b. Change in interaction between tuff and carbonate aquifers (increased upward flow or change to downward flow)

OTHER CONSIDERATIONS

- C. Hydrologic effects not dependent on tectonism but that could influence the effects of tectonic events or processes
 - 1. Climate-driven changes:
 - a. increased recharge /UZ flow
 - b. increased SZ flow/velocity
 - c. water-table rise in tuffs and/or head rise in carbonates
 - 2. Volcanism-driven changes:
 - a. ashfall on site changes infiltration rate and location
 - b. hydrologic effects of an intrusion through or near the repository
 - c. volcanism-created surface water impoundments.
 - 3. Coupling of volcanic and seismic events^a

^a This topic is not explored here. Please see the section Open Issues for remarks.

2.1 Reading the Event Tree and This Report

An event tree is located in the back of this report and should be consulted in conjunction with the reading of the section “Development of Tectonism Event Tree.” Figure 1 presents an overview of the event tree and provides a structural outline for the report.

Each scenario is built from a series of FEPs. Specific FEPs are indicated in the text by quotation marks. Each FEP is discussed in detail in the text, illustrated by a sketch and connected to following and preceding FEPs in the event tree. Text, sketches and tree segments are cross-referenced by means of sketch and tree segment numbers. Sketches which discuss FEPs may be distorted in proportion to enhance features of interest that might not be discernible if drawn to scale.

Small parts of the event tree, called tree segments, are reproduced in the text to aid discussion. A tree segment is a diagram in the text containing a set of branches excerpted from the event tree. The ellipses in the lowest tier of Figure 1 map the tree segments into the complete tree. For example, (TS1) refers to Tree Segment 1 in the text and to the left most branch of “New Fault Through Repository Block,” “Fault Penetrates Deeply into the Crust.” Figure captions trace the tree path from initiating process or event to the segment depicted in the figure. An additional purpose of each caption is to restate the assumptions upon which the discussion of the figure is based. The discussion will proceed by examining, in turn, each tree segment until all the pieces of the event tree have been explored.

3.0 THE EXPECTED ENVIRONMENT

The repository environment will evolve in time, altering the critical phenomena which must be considered in determining the response of the repository to tectonic processes. This response will also be dependent on design decisions - decisions which influence rock response close to the waste containers. The current description of the expected evolution of the repository is dependent upon interpretations from experiments and modeling. Further experimentation, like that being started in the Experimental Studies Facility (ESF) and further results from site characterization, may lead to revision of expectations of that evolution and, consequently, to revision of scenarios.

When openings are first mined or bored into the rock, the surrounding rock begins to relax into the openings. This relaxation may generate radial and concentric fractures affecting perhaps three drift diameters (Jaeger and Cook, 1979) (Figure 2), as well as movement along existing fractures. The rate of stress relief by fracture generation depends on the specific rock type and characteristics of the tuffs at Yucca Mountain. Hot waste containers will probably be emplaced in the drifts before much stress relief has occurred. Thermal loading (the local and the average power densities), container type (Multi-Purpose Container, MPC, or Site Characterization Plan, SCP, container), loading scheme and the use of backfill determine the thermo-mechanical and hydrothermal response of the rock.

The thermal load causes thermal expansion of the rock - expansion sufficient to possibly overwhelm the mechanical stress relief early in the life of the repository. Calculations by Jung and others (1994) indicate that zones of compression will form near the openings and zones of tension will form away from the repository, including all the way to the surface of the mountain. Compression is expected to close many, but not all, of the fractures leading to the underground openings (see Mack and others, 1989). Figures 3, 4, 5, from Mack and others (1989), give a qualitative perspective on the regions in which the apertures change and how that is affected by time. The thermal effects of stresses within repository units have been calculated for unfractured units (e.g., Hardy and Bauer, 1991). These calculations are based on laboratory measurements of the thermal expansion coefficient and thermal properties for the units at Yucca Mountain. These calculations indicate that the stresses remain compressive during the heating cycle. With the existing stress state of the mountain and the presence of fractures, thermal expansion is likely to produce shear on some fractures. Thermal expansion is expected to alter fracture permeability throughout the mountain and may extend to the surface.

Experiments have shown that the heating of some Yucca Mountain tuffs may result in substantial volumetric expansion of the rock.^{1,2} The volume increase locally may add to

¹ Brodsky, N. S., M. Riggins, J. Connolly and P. Ricci, in press. "Thermal Expansion, Thermal Conductivity, and Heat Capacity Measurements for Boreholes UE25 NRG-5, USW NRG-6, and USW NRG-7/7A," SAND95-1955, Sandia National Laboratories, Albuquerque, NM.

² Martin, R. J., J. S. Noel, M. Riggins, P. J. Boyd, and R. H. Price, 1996. "Thermal Expansion of the Paintbrush Tuff Recovered from Borehole USW SD-12 at Pressures to 30 MPa: Data Report," SAND95-1904, Sandia National Laboratories, Albuquerque, NM.

Figure 1 contains the first two horizontal layers of branchings of the tectonic event tree.

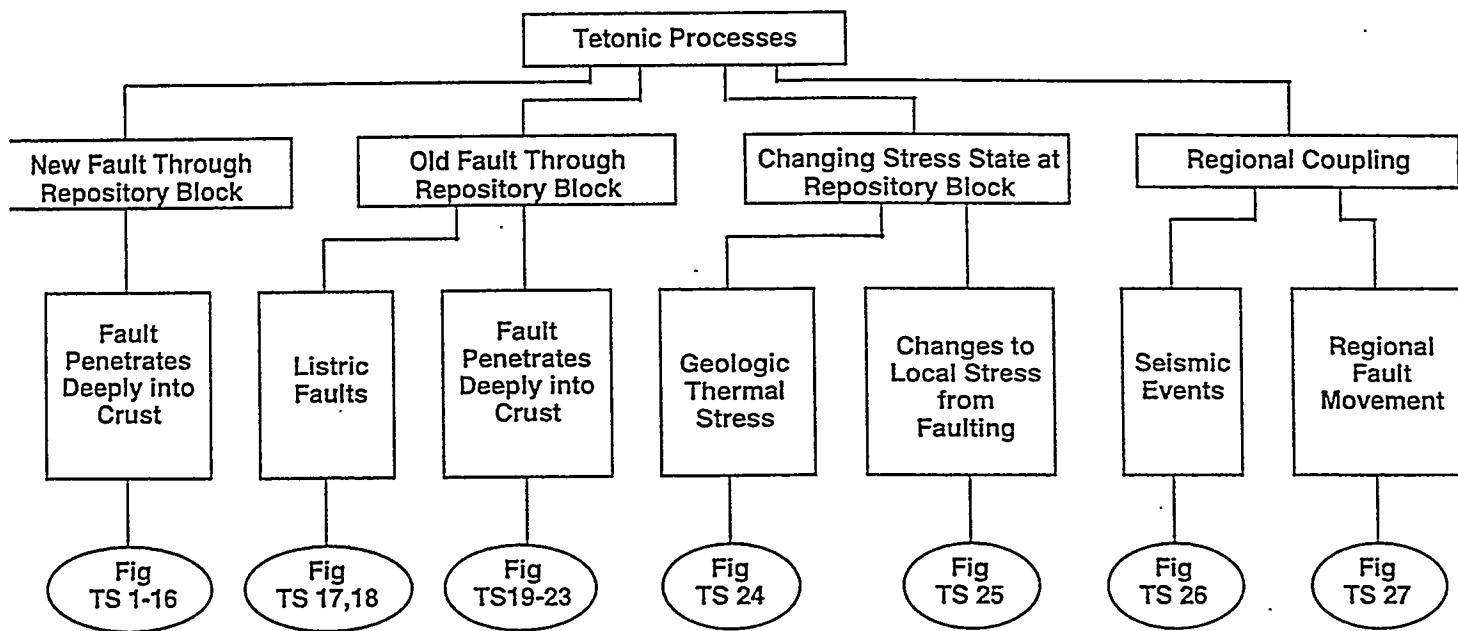


Figure numbers in Ovals indicate the figures containing an expansion of the associated box and thus approximate location of the accompanying text.

Figure 1. Tectonic Processes - Upper level tree illustrating the general structure of the event tree.

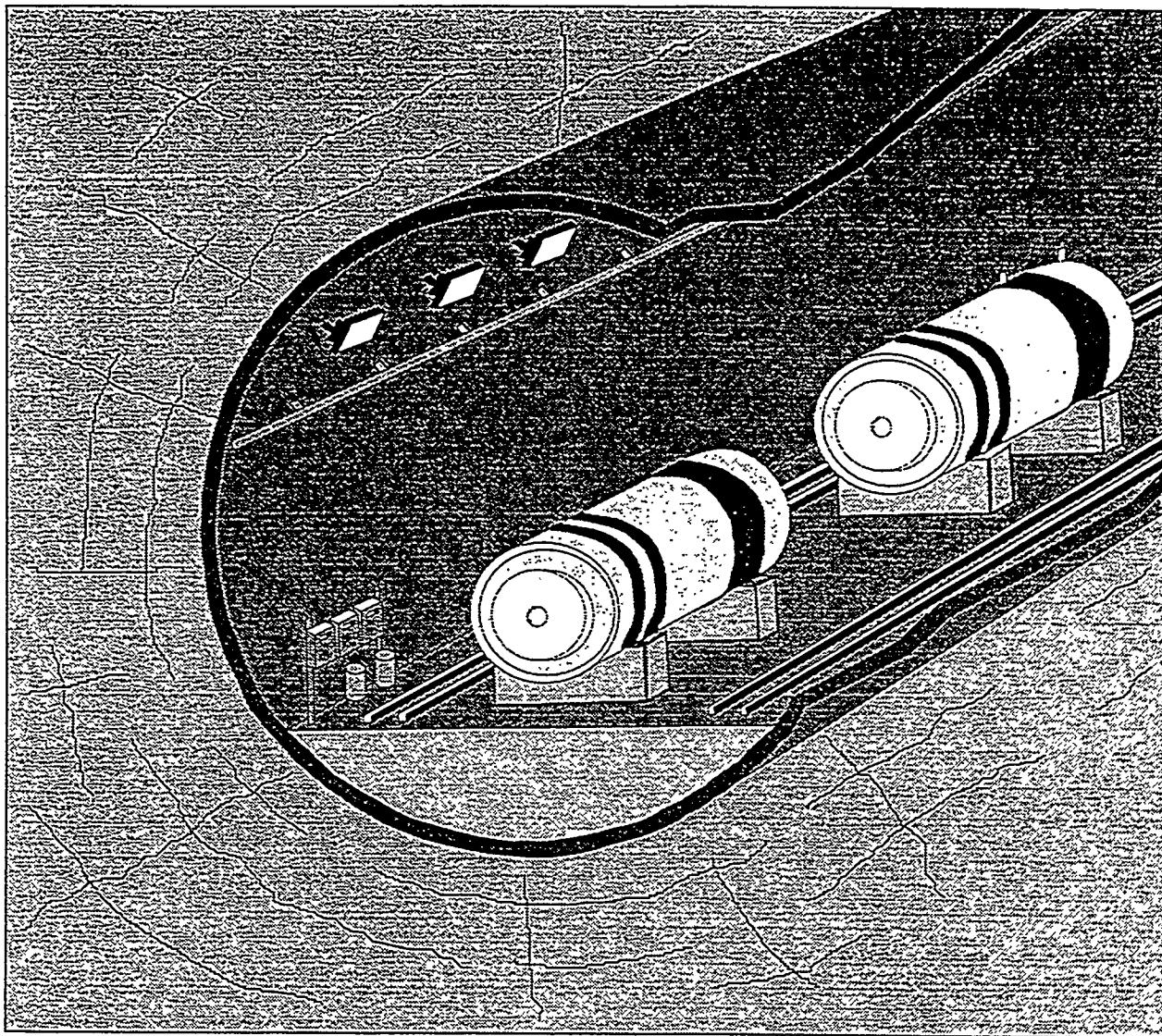


Figure 2. Conceptual design of a repository drift, with stress relief fractures shown in the rock.

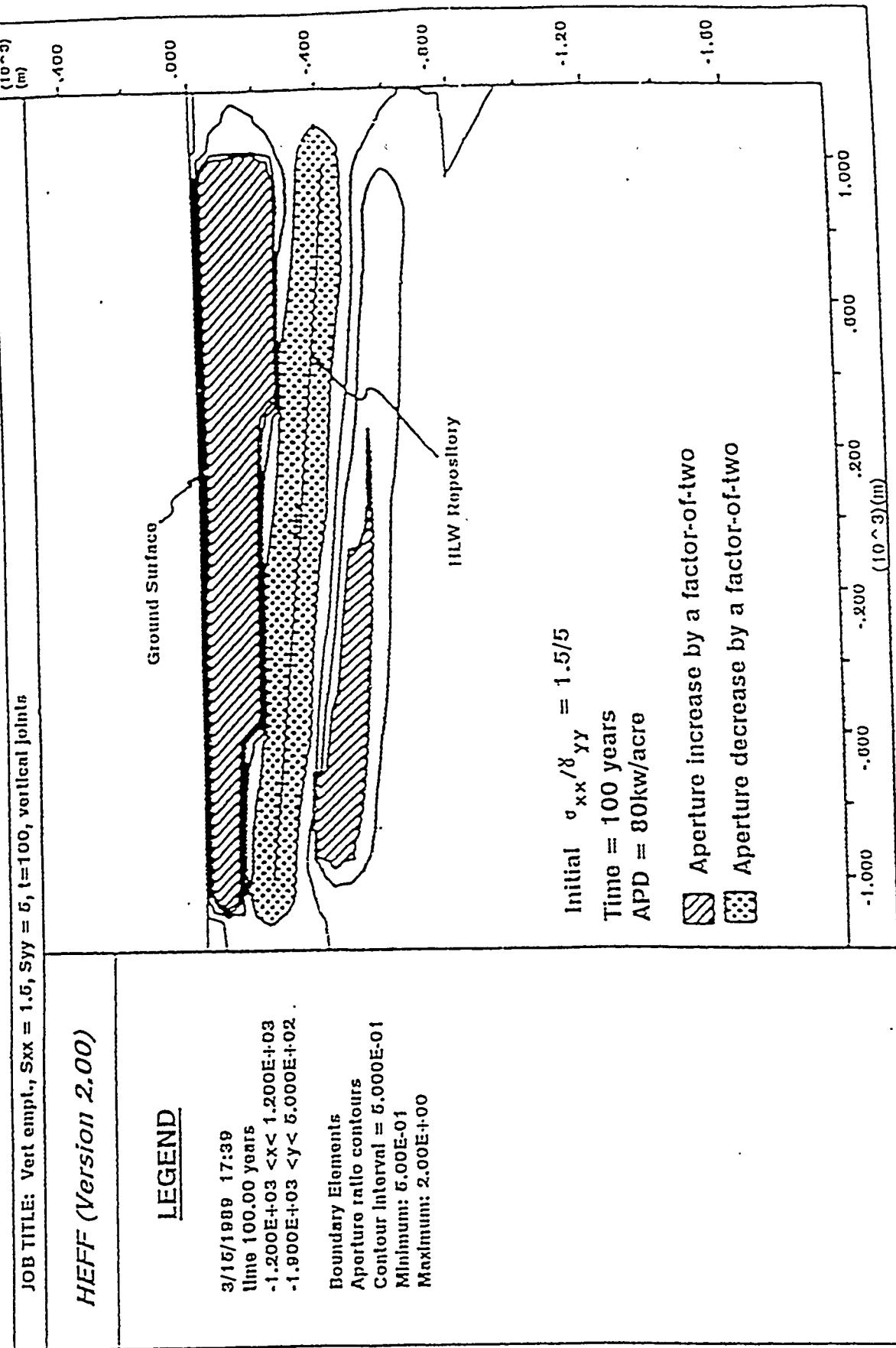


Figure 3. Regions of aperture change by a factor of two, 100 years after waste emplacement ($\sigma_{xx}/\sigma_{yy} = 1.5/5$)

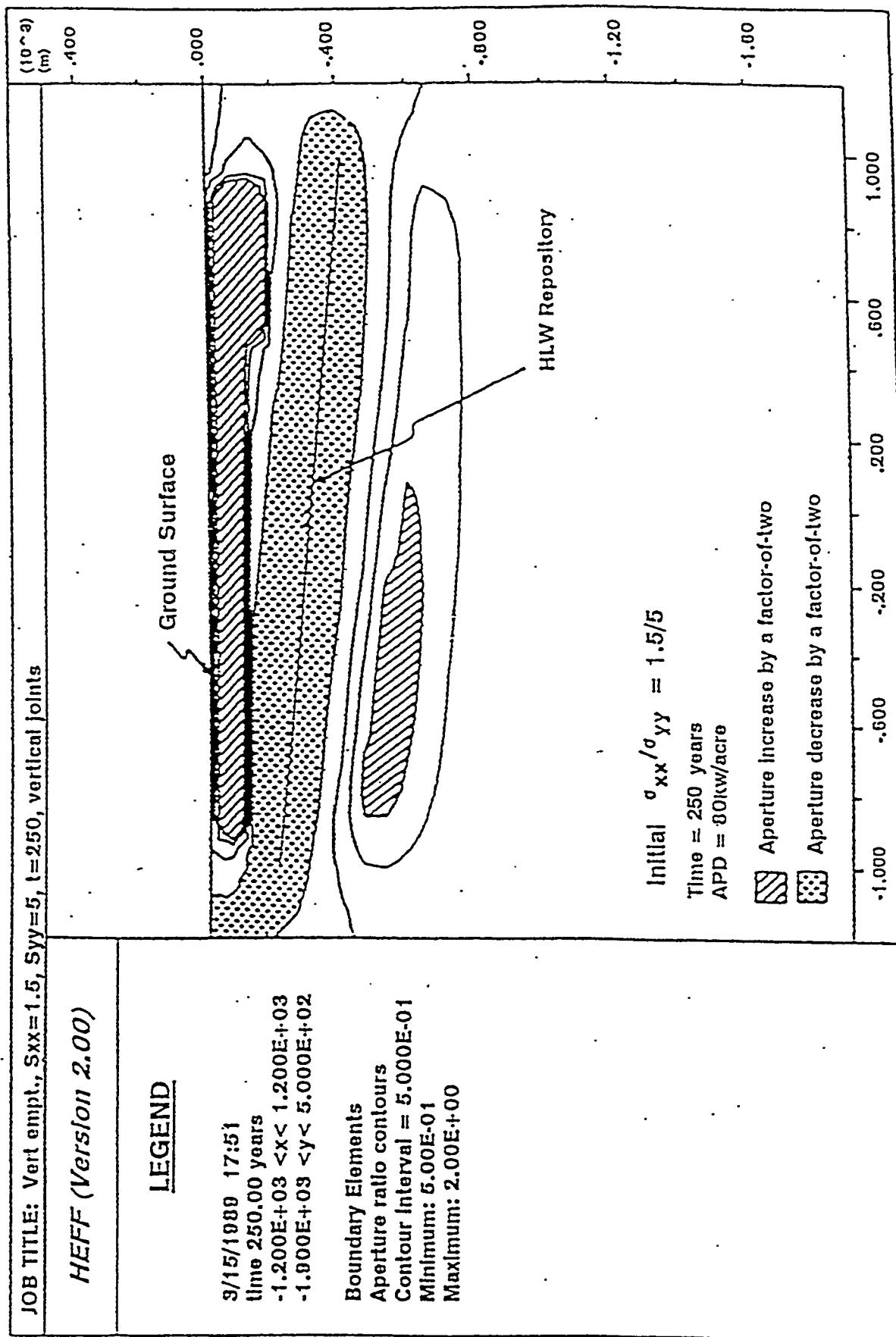


Figure 4. Regions of aperture change by a factor of two, 250 years after waste emplacement ($\sigma_{xx}/\sigma_{yy} = 1.5/5$)

JOB TITLE: Vert emlt, $S_{xx} = 1.5$, $S_{yy} = 5$, $t = 500$, vertical joints

HEFF (Version 2.00)

LEGEND

3/15/1989 10:05
Time 500.00 years
.1.200E+03 < x < 1.200E+03
.1.000E+03 < y < 5.000E+02
Boundary Elements
Aperture ratio contours
Contour Interval = 5.000E-01
Minimum: 5.00E-01
Maximum: 2.00E+00

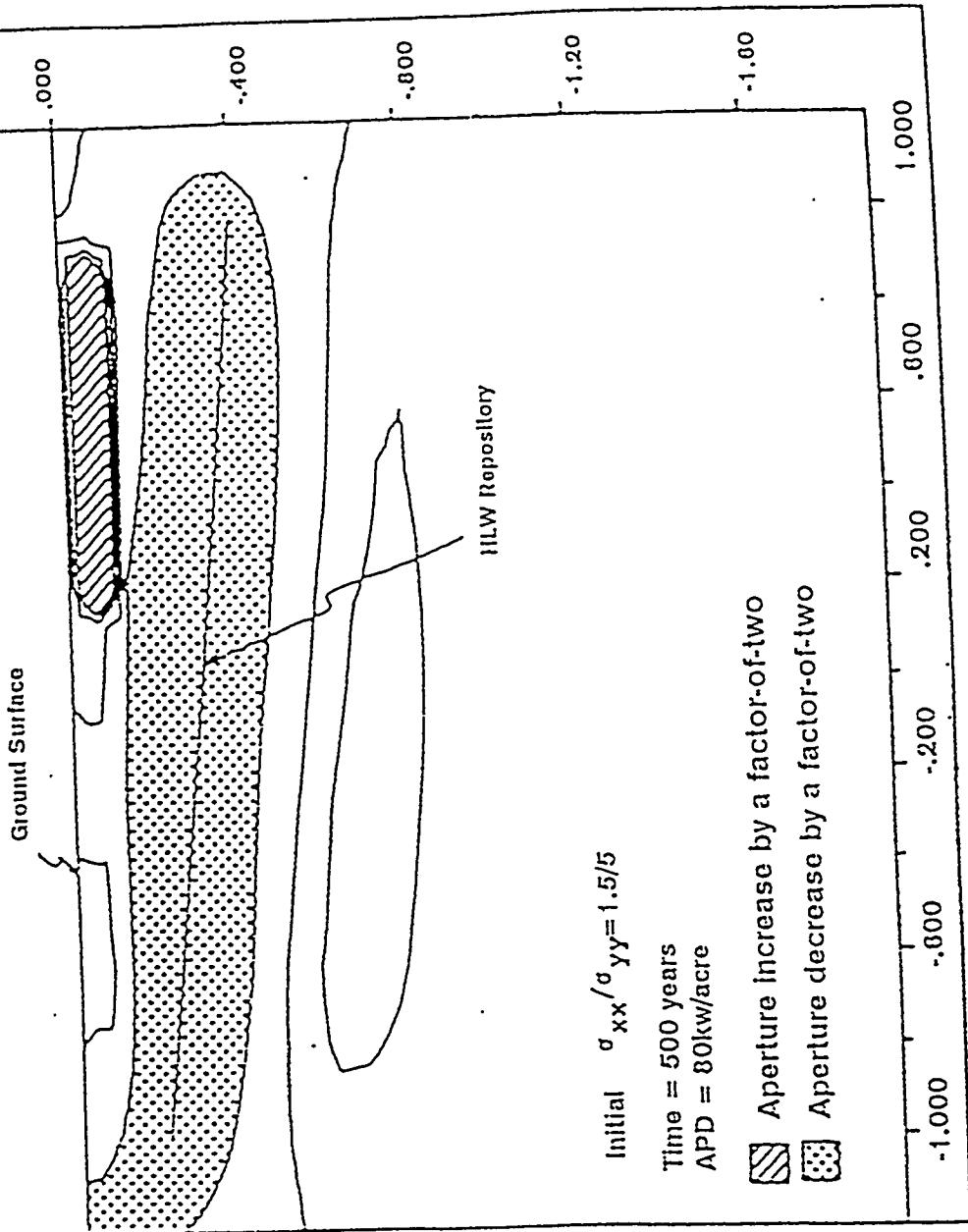


Figure 5. Regions of aperture change by a factor of two, 500 years after waste emplacement ($\sigma_{xx}/\sigma_{yy} = 1.5/5$)

the compression of the rock around the repository within the 150-C isotherm. Although this contributes to the compressive sealing of fractures during the early thermal period, it may also reduce rock integrity when the repository temperature declines.

The thermal load also generates flow of moisture and gas in the rock. Water vapor flowing into the drift will initially be removed by the ventilation system. After sealing or closure of a drift, the flow of vapor is confined to the rock. Extensive calculations using smeared heat sources to represent the repository have illuminated the possible importance of two-phase flow of water driven by the repository heat (Nitao, 1988, 1989; Tsang and others, 1993; Pruess and Tsang, 1993, 1994; Buscheck and Nitao, 1992, 1993; Nitao and Buscheck, 1989). The calculations suggest that for hundreds of years, depending on thermal loading and percolation, this two-phase flow will dominate water movement in the mountain. Heat-driven circulation of moisture, as modeled, has been about an order of magnitude greater than flux of water from the surface, for this period. The heat load suffices to affect the temperature and circulation of liquid water in the water table aquifer 200m or more below the repository. Heat and the flow of moisture are also expected to chemically alter the vitric Topopah Spring unit, below the repository but above the water table, causing conversion to clays and zeolites and possibly welding fractures and faults.

Few of these two-phase calculations examine the details of flow near containers, where the water-rock interactions with solutes having temperature-dependent solubilities need to be considered. According to B. Robinson³ recent modeling of these interactions on the repository scale (smeared source in homogeneous media) shows precipitation and dissolution at the evaporation and condensation zones of a heat pipe. This suggests rapid blockage of pores and fractures near the repository and diversion of flow further away. Earlier experiments (Lin and Daily, 1989) suggested a reduction of fracture aperture by dissolution of fracture asperities. Smeared source calculations support the formation of a condensate zone outside the vaporization isotherm (for water). Because vaporization in a fractured porous medium can involve a number of processes, "vaporization isotherm" is introduced to indicate the spatial location beyond which condensation from two-phase flow can occur. Individual container calculations and row (smeared source) calculations honoring repository layout geometry and real waste streams, using conduction models, show considerable structure to the vaporization isotherm (Ryder and Dunn, 1995). This raises the possibility that a condensation zone over one drift or part of a drift could shed to another drift or another part of the same drift, if the flow pathways were open. Sealed or blocked flow systems could be disrupted or reactivated by seismic processes.

Substantial percolation of fluids originating at the surface has the possibility to extinguish heat pipes and suppress the location of any condensate zone by moving it closer to the repository. Such occurrences have not yet been well explored in modeling. Some scenarios of this variety were mentioned in the "Nominal Flow" document (Barr and

³ Robinson, B., C. Gable, and G. Zyvoloski, 1995 (in technical review, to be published), "Summary of Recent Retardation Sensitivity Analysis Activities, Yucca Mountain Site Characterization Project," Milestone Number 3416, LA-EES-5-TIP-94-001, R1, Los Alamos National Laboratory, 43 p.

others, 1995). If data support this possibility, scenarios presented here will need to be reexamined. Thermal effects, which may appear in rocks all the way to the surface, have additional consequences below the repository. Two-phase calculations (Buscheck and Nitao, 1993) and conduction calculations (Jung and others, 1994) indicate that the water table is not an isothermal boundary. These calculations indicate the possibility of temperatures in excess of 60° C at the water table, suggesting that single-phase convective flow might be established. Differential solubilities of silica over the 30° C or so available to drive the convection would be expected to produce a mass transport to some depth below the water table. Precipitation could then plug the flow system, both pores and fractures, again raising the possibility of tectonic processes altering or reactivating transport.

The description of the evolution of the environment has so far considered only the immediate changes due to emplacement of hot waste containers. These heat sources are not constant; they decay exponentially in output from the time of emplacement. For most of the 10,000-year regulatory life of the repository, cooling occurs mostly by propagation of heat into the rock. The mechanical response to this cooling of the repository is diffusion of thermal expansion throughout the mountain. Because most of the heat is still retained in the mountain during the 10,000-year lifetime, the net thermal expansion is about the same, but the strain (actual movement on fractures) is redistributed over the entire heating period. In particular, cooling near the drifts will allow rock fall into the drifts. Roughly speaking, over 10,000-15,000-years the drifts will gradually fill with rock (Gauthier and others, 1995). Tectonic processes are expected to increase the rate of filling of the drifts (see, for example, Ahola and others, 1995; Blejwas, 1989; Hardy and Bauer, 1991).

Assumptions

Because no final design decisions have been made and because certain decisions alter how tectonic processes affect scenarios, we have made certain assumptions about design. We have assumed that there will be horizontal, in-drift emplacement of an MPC without backfill, in a lined drift, with an invert of crushed tuff supporting a rail system (Figure 2). If designs are altered, it is necessary to check how the scenarios change. For example, use of backfill around the MPC could ensure a sufficiently good coupling with the surrounding rock such that shear of a container by a through-going fault becomes an issue.

4.0 PRELIMINARY CONCEPTUAL MODEL OF FAULTING

Geologic field studies to characterize the magnitudes, recurrence rates, and styles of faulting and related tectonic deformation at Yucca Mountain are, as yet, incomplete. A current major gap in these studies is development of a conceptual model of faulting in the Yucca Mountain region that is specifically tailored to form the basis for hydrologic and engineering characterizations of the faults, including the magnitude and nature of deformation, and the resulting changes in rock properties that are anticipated in a single faulting event. The following is, therefore, a preliminary statement that summarizes the current state of knowledge and the issues that need to be addressed.

Large-Scale Structural Geometry of the Yucca Mountain Area:

The Yucca Mountain region is located in southern Nevada in the southwestern Great Basin (Figure 6). Yucca Mountain itself is an arcuate, multiple-fault-block ridge that extends around the north, east, and south flanks of the Crater Flat alluvial basin (Figure 7). This arcuate ridge and the “flat” it near encloses are structurally linked (Figure 8); together, they constitute a single domain in terms of their structural style and tectonic history, and they are distinct in these features from adjacent structural domains (Fridrich and others, in press) in terms of overall fault pattern. The Yucca Mountain/Crater Flat domain is an asymmetric graben of sorts because it is bounded by the east-dipping Bare Mountain range-front fault on the west side and the vast majority of faults within the basin are antithetic faults in the sense that they face into the range-front fault and are coeval with it (Fridrich and others, in press), as shown in Figure 8. In addition, this domain apparently is bounded on the east side by a major concealed west-dipping fault (Figures 7 and 8), commonly known as the Gravity fault (Winograd and Thordarson, 1975). Thus, as a structural feature, the Yucca Mountain/Crater Flat domain is more like a structural basin than like any other type of named structural feature, despite the uplifted ridge (Yucca Mountain) that forms a major part of it. For simplicity, this domain is hereafter referred to as the Crater Flat basin. Based on gravity data (Blakely and others, 1995), this basin is the northernmost in a series of three contiguous basins that together constitute the central Amargosa trough, a large graben-like feature that extends from the Timber Mountain caldera complex southward to the Furnace Creek fault (Figure 7).

The Crater Flat basin is one of numerous extensional basins of differing sizes, shapes, and structural styles that lie within the Walker Lane belt (Figure 6). Herein, we apply Stewart's (1988) nongenetic definition of the Walker Lane belt as the 100-to-300-km-wide by 700-km-long northwest-trending zone of irregular topography and discontinuous strike-slip structures that intervenes between the Sierra Nevada and the northern Basin-and-Range province. The Crater Flat basin also lies along the southern flank of the southwest Nevada volcanic field (Figure 6). The major ash-flow sheets of the volcanic field form the major fill of the Crater Flats basin, including the upper 1.5 to 3 kilometers of Yucca Mountain over a substrate of paleozoic sedimentary rocks. Like the rest of the Walker Lane belt, the Yucca Mountain region consists of a mosaic of domains that are separated from one another by structures or zones across which abrupt, fundamental changes are present in the style, timing, and magnitude of extension and other deformation.

Normal faults within Crater Flat basin have strikes that are northerly in the northeastern part of the basin, changing to increasingly northeasterly strikes to the south and to the west across the basin (Figures 8 and 9). Strata within the basin dip into the closely spaced intrabasin normal faults, forming a tilted-domino structural style (Figure 10). The magnitude of faulting and tilting in the basin increases to the south and to the west from

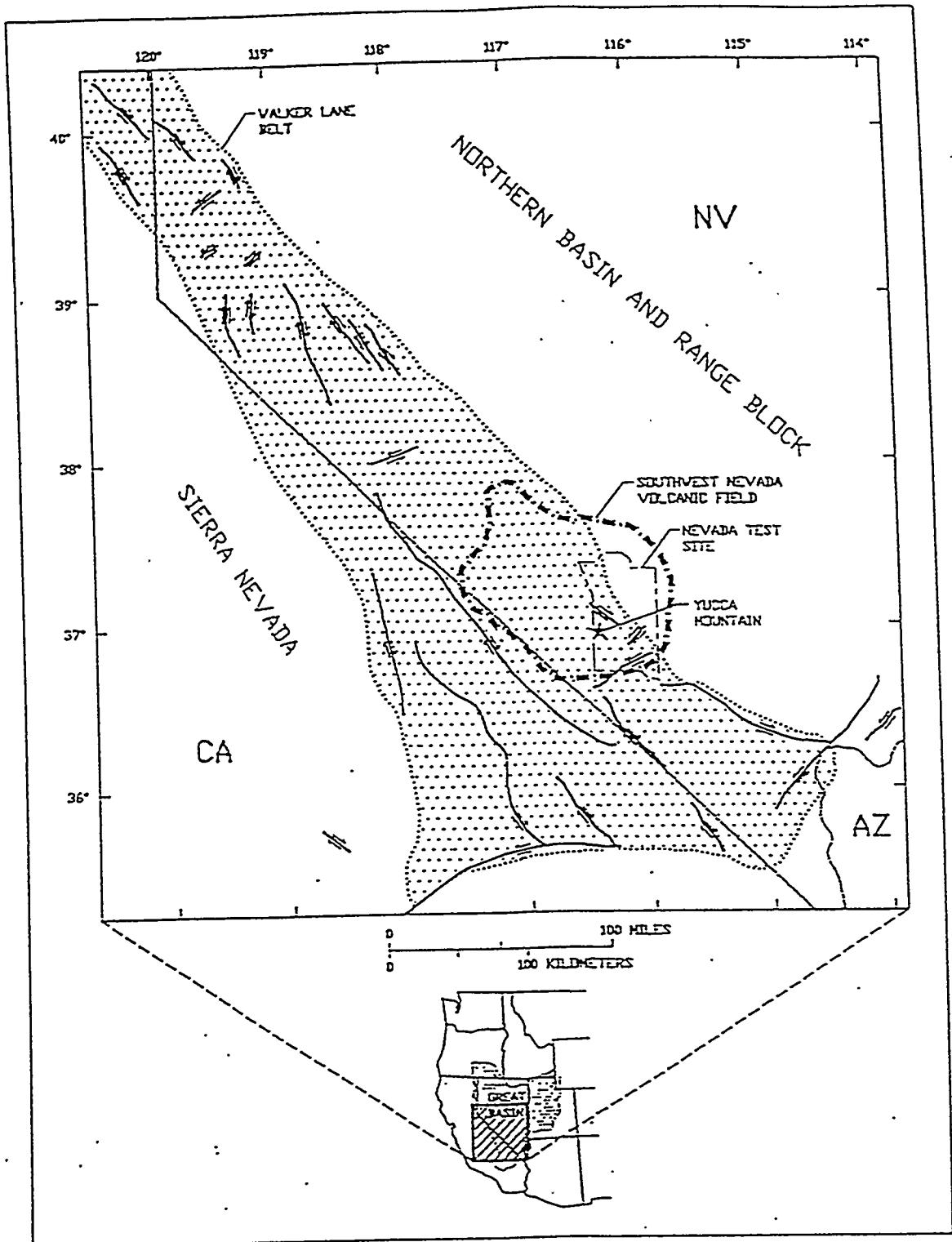


Figure 6. Location map of Yucca Mountain (star) in the southwest Nevada volcanic field (Broxton and others, 1989) of the western Great Basin, with schematic representations of faults of the Walker Lane Belt that have strike-slip components of offset (dip-slip offsets not shown) modified from Stewart (1988).

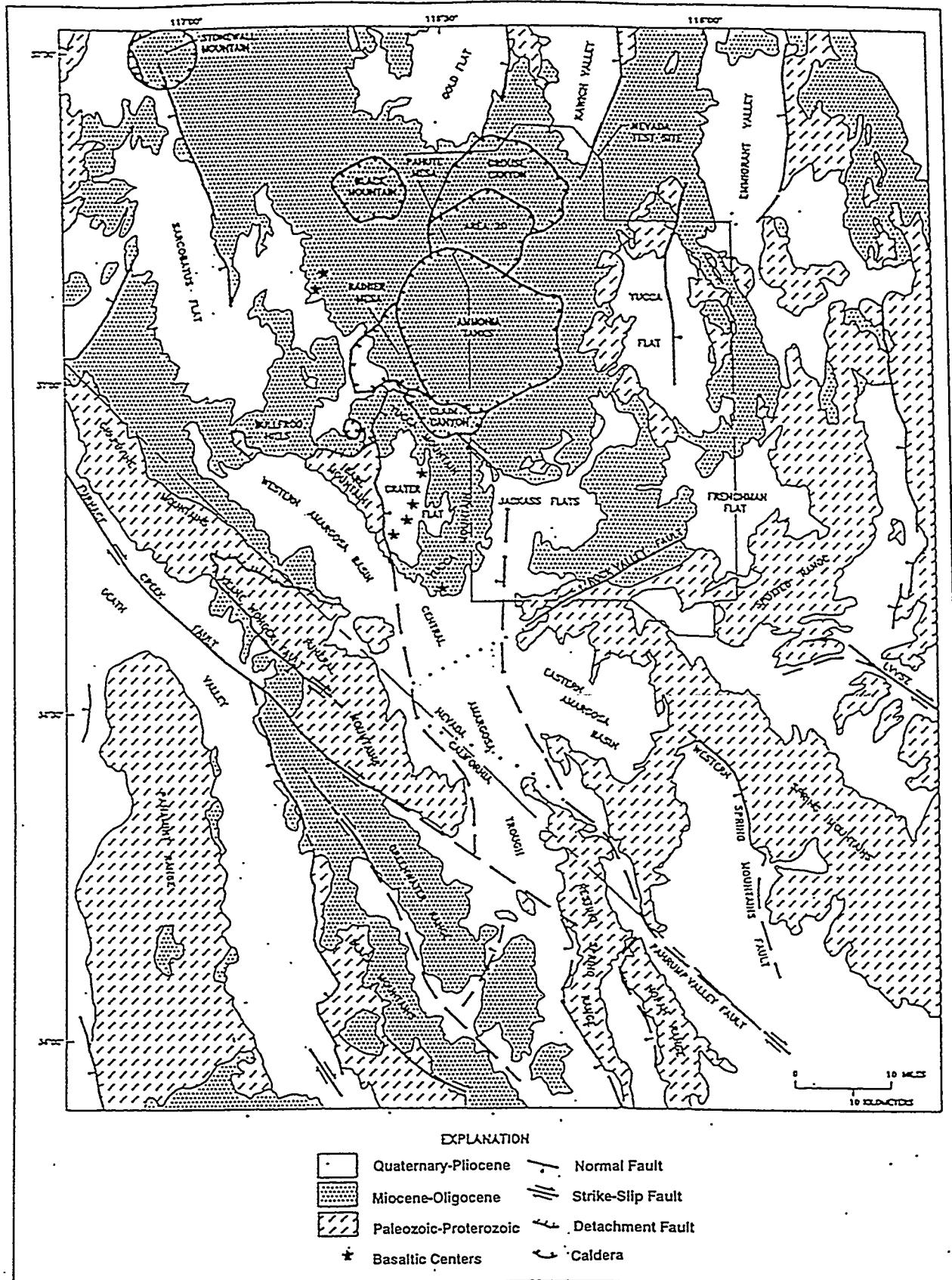


Figure 7. Generalized map of the Yucca Mountain region showing major physiographic features and selected faults; compiled from Jenkins and others, 1962; Longwell and others, 1965; Cornwall, 1972; Streitz and Stinson, 1974; Ekren and others, 1977; Burchfiel and others, 1983; Wright, 1989; Frizzell and Shulters, 1990; Picty, 1993; Sawyer and others, 1994.

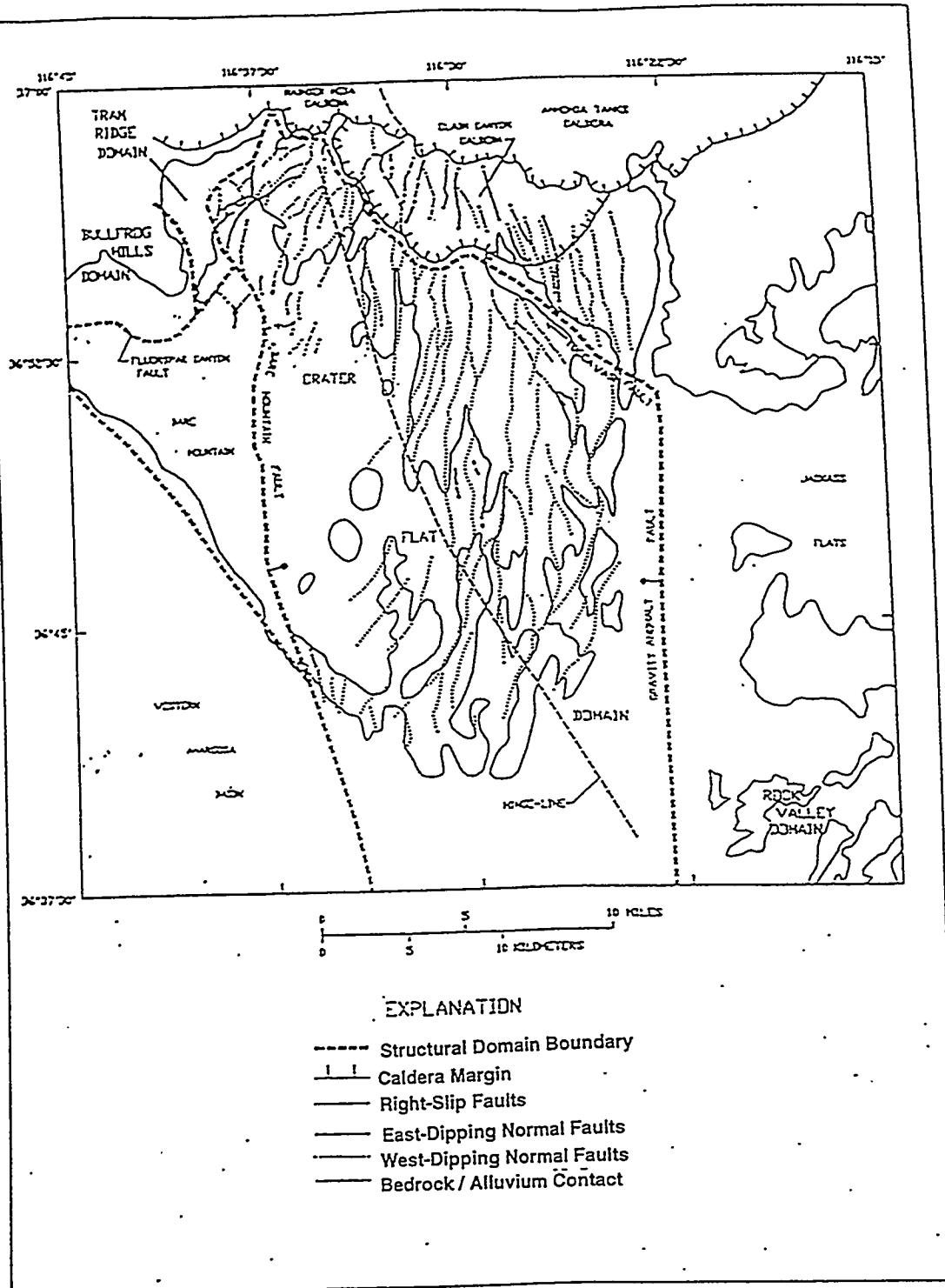


Figure 8. Map showing structural domains and domain boundaries of the Yucca Mountain region and internal fault patterns of the Crater Flat basin and selected parts of adjacent domains, compiled from Monsen and others, 1992; Simonds and others, 1995; and Fridrich and others, in press.

the point of minimum extension in the northeastern corner of the basin (northern Yucca Mountain), indicating that the basin opened somewhat like a Chinese fan, with caldera complex as a pivot point. This geometric style of oblique extension resembles that of triangular and rhombic pull-apart basins.

The oblique pattern of extension within Crater Flat basin is accompanied by orocinal bending across the basin, which has been documented with paleomagnetic data (Rosenbaum and others, 1991; Hudson and others, 1994). These data indicate that the curved pattern of faulting down the east side of the basin (southward across Yucca Mountain; Figures 8 and 9) reflects southward-increasing clockwise rotation. The radial pattern of faulting around the caldera complex is partly a primary feature that reflects distortion of the regional tectonic stress field in the vicinity of the subcaldera magma chambers (Christiansen and others, 1965). This primary pattern has, however, been strongly accentuated by westward-increasing clockwise rotation across the northern part of the basin (M. Hudson, unpublished data).

Within the Crater Flat basin, a northwest-trending "hinge-line" can be discriminated that separates an area of predominantly north-striking faults to the northeast, from an area of predominantly northeast-striking faults to the southwest (Figure 8). Based on aeromagnetic data, the hinge-line corresponds approximately to the contour of 200 clockwise rotation of the Tiva Canyon tuff; greater than 200 of rotation is present to the southwest of this line and less to the northeast (Rosenbaum and others, 1991; Hudson and others, 1994; Hudson, written comm., 1995). A subtle, but abrupt topographic decline (lower on the southwest side) is present along most of the length of the hinge-line, reflecting a southwestward increase in the magnitude of extension.

In that the southwestward-increasing pattern of clockwise rotation across the Crater Flat domain constitutes a zone of oroflexural bending (a fold), the inflection in fault strikes which define the hinge-line is apparently the axis of the fold. The zone of bending extends across to the Bare Mountain range-front fault; however, the Bare Mountain domain was not significantly rotated during the opening of the Crater Flat basin, based on existing aeromagnetic data (Hudson and others, 1994; Hudson, written comm., 1995). The area between the hinge-line and the range-front fault constitutes a transtensional structural zone and is the area of greatest extensional and strike-slip deformation in the basin. Nearly all of the basalts of the Crater Flat basin have been erupted from within this transtensional zone, suggesting that the volcanic activity is structurally controlled (Fridrich and others, 1994b).

Nearly all of the north to ~northeast-trending normal faults within Crater Flat basin show a component of left-oblique offset. Left slip on these intrabasin faults is consistent with the clockwise rotation of the blocks between the faults, and from that perspective, is indicative of dextral shear throughout the basin. Given the late Cenozoic-stress regime of the Great Basin, with the least principal stress-oriented west-northwesterly, on average, the resolved sense of strike-slip shear on north- to northeast-trending normal faults is right lateral (Figure 10A). However, when the blocks between faults are rotating

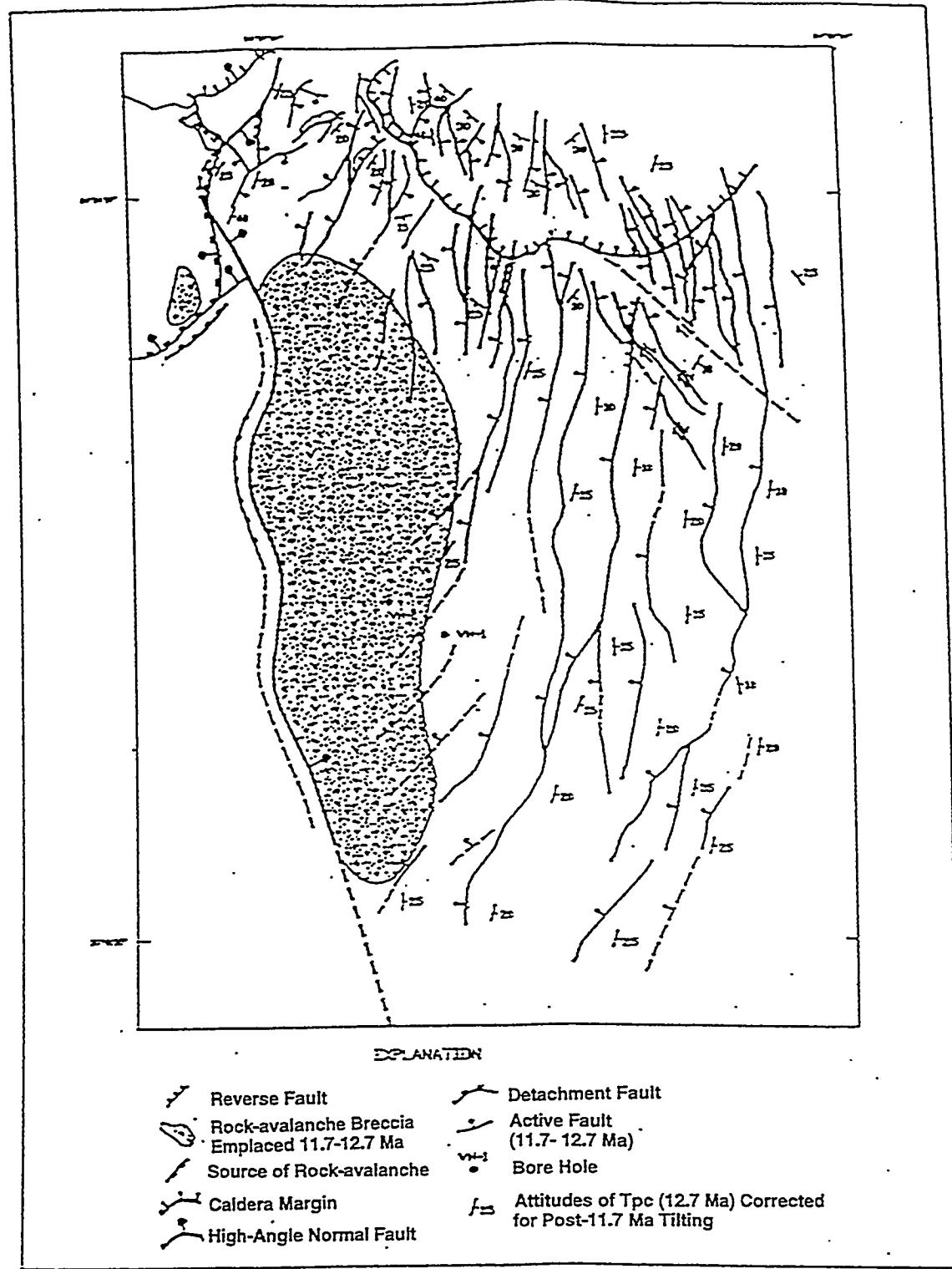


Figure 9. Map showing features relevant to tectonic activity from 12.7 to 11.7 Ma in Crater Flat basin and vicinity. Faults in Claim Canyon caldera are predominantly related to caldera resurgence which occurred between 12.7 and 12.5 MA. Dips in the Claim Canyon caldera reflect resurgent doming structure of the cauldron block. Faults shown in Crater Flat basin are ones known to have been active in this interval based on angular unconformities between the 12.7 Ma Tiva canyon Tuff, the uppermost unit of the Paintbrush Group, corrected for tilting after 11.7 Ma; with that correction, these attitudes represent the degree angular unconformity between the Paintbrush and Timber Mountain breccias formed in this time interval. Map data compiled from Christiansen and others, 1965; Scott and Bonk, 1984; Fridrich and others, in press; Scott, unpublished data.

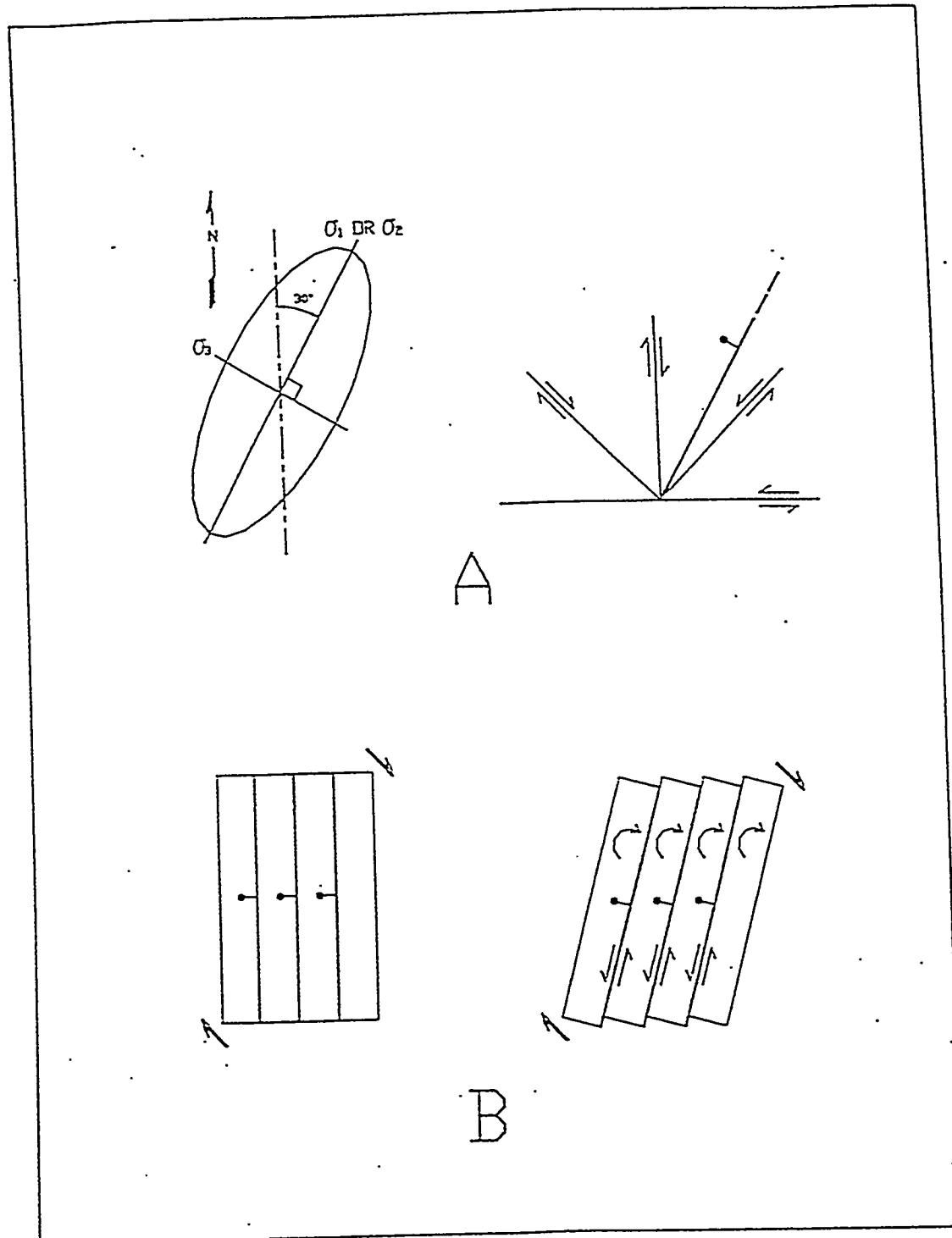


Figure 10. Schematic illustrations of (A) resolved sense of strike-slip shear on faults having a range of orientations, given a representational stress ellipsoid for the western Great Basin, and (B) illustration showing the dynamic sense of strike-slip shear along originally north-striking faults when the same stress regime results in vertical-axis rotation concurrent with extension.

clockwise in response to this dextral shear stress, the horizontal component of movement on the normal faults then has the opposite shear sense (left-lateral), reflecting dynamic shear (slip that accommodates rotation; Figure 10B), rather than the static sense of shear.

In summary, the Crater Flat basin is a hybrid structural feature, reflecting three major influences: (1) east-west to northwest-southeast extension, (2) northwest-directed dextral strike-slip deformation, and (3) the effects of the caldera complex at the northern boundary of the basin, which includes: (a) doming and related distortion of the stress field around the caldera complex when it was active (from >12.7 to 11.4 Ma), and (b) an apparent pinning effect in which the caldera complex acted as a pivot point for oblique extension within the basin. This mixture of influences is consistent with the setting of this basin on the flank of a caldera complex that was active during its formation, and within the Walker Lane belt near the boundary between this province, which is characterized by both strike-slip deformation and extension, and the northern Basin-and-Range province, which is characterized by more purely extensional deformation.

Determining the significance of the strike-slip deformation in the Crater Flat basin, with respect to the basin's origin and to seismic risk assessment for the Yucca Mountain site, will require taking a more regional view than has been taken in existing tectonic studies.

Tectonic Evolution of the Crater Flat Basin

The Crater Flat basin initially formed between 12.7 and 11.7 Ma in a large extensional pulse which began in the center of the southwest Nevada volcanic field near the peak phase in eruptive activity (Sawyer and others, 1994; Fridrich and others, in press). This major extensional pulse marked the beginning of an interval, extending to the present, in which the focus of maximum extension has migrated progressively westward across the Yucca Mountain region. In any one area, the trend observed during the regular westward migration is one of abrupt onset of a pulse of rapid extension, followed by a progressive decline in extension rate. Scattered small domains, including a major part of the Crater Flat basin, have remained tectonically active at feeble rates long after passage of the extensional pulse.

Developing quantitative estimates of the rates of extension in the Crater Flat basin over time, from the initiation of the basin to the present, will be difficult for three reasons. First, methods of estimating the percentage of extension vary depending on assumptions made about the structural style of deformation, and the structural style in the Crater Flat basin has progressively changed during its evolution. Specifically, fault spacing has effectively increased with time because activity has become progressively focused on an ever smaller number of the most major faults. Second, at the same time, the rate of tilting has apparently decreased, both in an absolute sense and relative to the rate of offset along the active faults. Third, in addition, the area of continued tectonism has been progressively shrinking; whereas the 12.7-to-10 Ma peak phase of tectonism involved strong deformation throughout the Crater Flat basin, since 10 Ma the northwestern part of the basin has become inactive and the bulk of the Quaternary activity is concentrated in the south-central part of the basin. Further, stratigraphic units younger than 10 Ma are poorly exposed in the basin and are difficult to date; hence, there are large uncertainties in

the constraints on the waning phase of tectonic evolution of the Crater Flat basin. Studies documenting Quaternary activity along the major fault systems in the east and central parts of the basin (Menges and others, 1994; Ramelli and Whitney, oral comm., 1995; Figure 11) show the same pattern of southward increasing offset rates that has been true for this basin throughout its evolution. These studies also show that the 12.7-to-10-Ma pattern of left-oblique slip along these faults has continued to the present; (the Crater Flat basin is still opening like a sphenochasm or rhombic pull-apart basin.). Evidence of recent offset on all of the quaternary faults within the basin ends across the ridge that bounds the southern margin of Crater Flat physiographic feature (Figure 8). The Crater Flat basin has thus been an isolated pocket of faulting activity in the late Quaternary; there is no evident master structure that connects the recent tectonism in this basin to that in any other part of the region.

In the Pliocene and Quaternary, the highest rates of faulting activity have been along the southern parts of the fault systems in the eastern part of the basin; hence, the 3.7 and 0.1 Ma basalts apparently formed in that part of the basin that was most tectonically active at the time (Figure 11). The 10 Ma basalts of Crater Flat also erupted in that part of the basin that was most tectonically active at that time (Fridrich and others, in press). There is some evidence that suggests that seismic activity in the Crater Flat basin may be episodic and may have risen and fallen with episodes of recent volcanism; however, more study is needed before a firm conclusion can be reached on this issue.

Proposed Tectonic Models for the Yucca Mountain Region

The name Crater Flat basin and the above definition of this feature are derived from Fridrich and others (in press), which is the source of the above synthesis. The published alternative conceptions of the tectonics of the Yucca Mountain region are too numerous to review in detail, but they can be summarized in three end-member categories, according to the dominant process that is used to explain the major structural features of the Yucca Mountain/Crater Flat domain. According to one theory, Crater Flat formed as a caldera complex (Carr, 1982; Carr and Parrish, 1985; W. Carr and others, 1986; Carr, 1988, 1990). A second hypothesis is that Crater Flat is part of a rift that extends through the central part of the Amargosa Desert to the south (the central Amargosa trough; Figure 7), and that is genetically related to strike-slip faulting of the Walker Lane belt (Schweickert, 1989; Wright, 1989; Carr, 1990). The third end-member explains the structural features of Crater Flat and Yucca Mountain as being the result of detachment faulting (Hamilton, 1988; Scott, 1990).

A common element in the three published end-member theories for the tectonics of the Yucca Mountain/Crater Flat area is that they invoke a dominant controlling structure that is somehow concealed. If unequivocal exposures of a caldera, a master strike-slip fault, or a detachment fault existed in the Crater Flat basin, there would not be the latitude for the broad differences of opinion that exist on the tectonics of this area. The fact that these

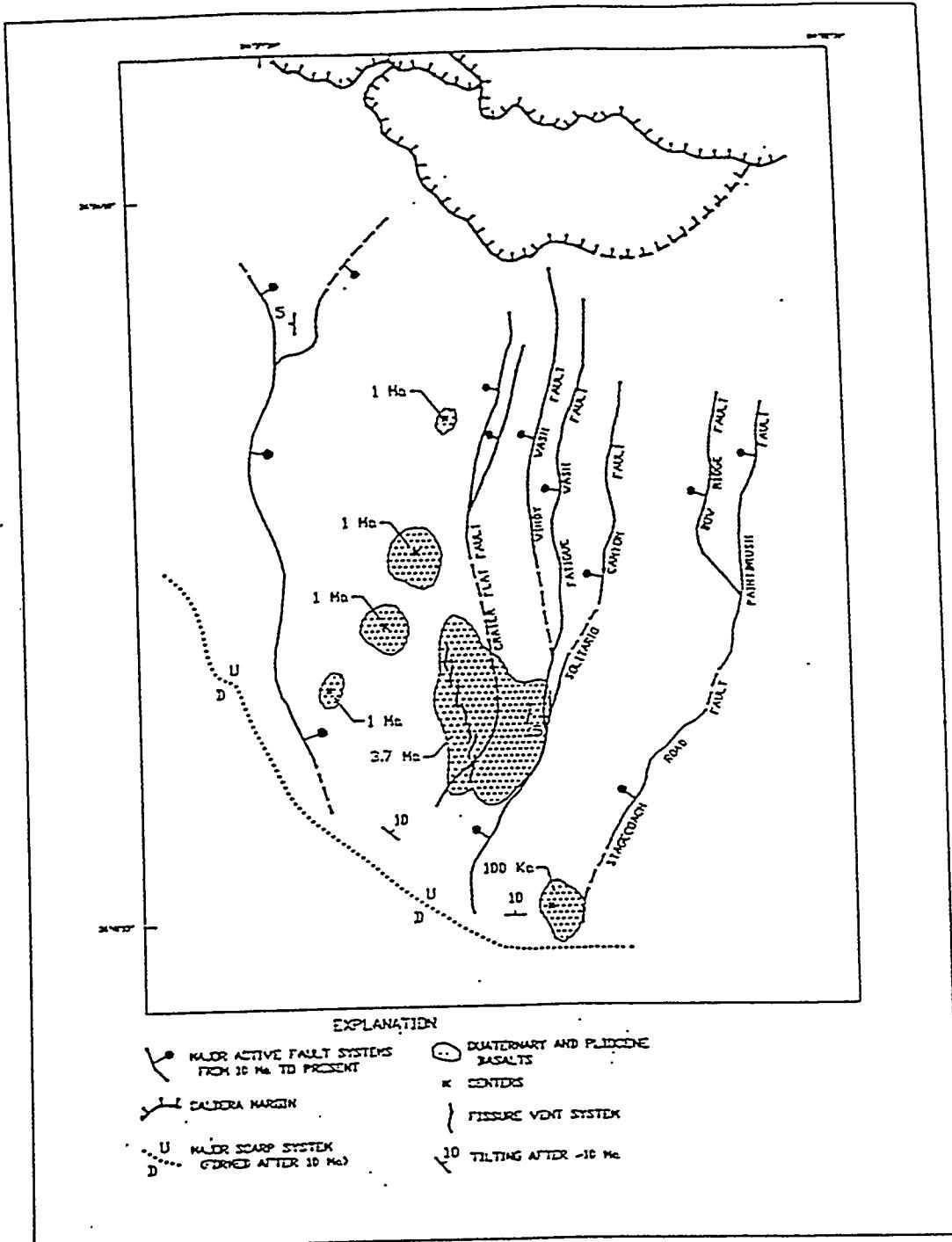


Figure 11. Map showing features relevant to tectonic activity from about 10 Ma to the present in Crater Flat basin, including tilting, and basalts erupted.

end-member theories invoke concealed master structures makes them difficult to test. For the purposes of this report, however, what we need from a tectonic model is something rather different from what these published theories provide. There are only two alternative conceptions that are of critical importance for the present analysis: (1) the faults we see at the surface penetrate deeply into the crust and (2) the faults we see at the surface terminate into an upper crustal structure, such as a detachment fault, which is located at a depth shallower than the effective base of the hydrologic system under Yucca Mountain. Both of these alternatives are carried in the scenarios.

Nature of Deformation in Individual Fault Zones

Geologists commonly depict faults as simple planar features on maps and cross sections, they are usually shown as thin lines. The reality, of course, is that faults, like all breaks in brittle, heterogeneous materials, are complex in their detailed geometry. Geologic studies usually focus on these geometric details only to the degree that they are significant at the scale that particular field study is being conducted, and that scale most commonly is large. Many of the smaller-scale details of fault complexity may, however, be the dominant features of concern for characterization of the hydrologic and engineering properties of fault zones.

Detailed studies of the fault zones in the vicinity of the potential repository area at Yucca Mountain are at a preliminary stage of development. Much useful information could be synthesized from available publications describing the results of detailed fault studies conducted in other localities. Interpretation of the detailed fault studies at Yucca Mountain need be integrated with a synthesis of this type. However, that synthesis task is also at a preliminary stage of development. Hence, the following is just a first cut in the development of the conceptual model for the nature of fault zones at the Yucca Mountain site.

Faults are fractures that form by shear failure of rocks and that incur significant displacement strain across them (Anderson, 1951). Normal faults, such as those at Yucca Mountain, form with their strikes oriented perpendicular to the least principal stress and dips roughly in the plane of maximum shear stress. Given that the least principal stress is almost always horizontal for most rock types, the maximum shear stress will be at an angle of 50 to 70 degrees from the horizontal based on empirical measurements and, consequently, normal faults typically form with dips averaging about 60 degrees. Nucleation of new faults is thought to occur by exploitation of existing cracks or other defects in the rocks; hence, faults initiate as large collections of individual cracks which propagate and merge together to form a large-scale fracture plane. The merging process commonly is imperfect or incomplete, however, and faults therefore typically have a segmented character (Figure 12).

Moreover, in many cases, the individual cracks that propagate to form a fault do not all lie in the same plane; hence, most faults are really fault zones which consist of numerous parallel or en echelon segments or strands (Figure 12). Further, the individual strands

may be subparallel rather than parallel, and the common result, in that case, is a fault zone with anastomosing strands, which could be characterized as a braided pattern. This type of complexity is commonly developed in a fractal manner; for example, large-scale faults may together form segmented and/or anastomosing patterns that resemble the patterns formed on a small scale by the strands within individual fault zones (Figures 12 and 13), (Hobbs and others, 1976; Ramsay and Huber, 1987; Brown and Scholz, 1985; Aviles and others, 1986; Lin and others, 1993).

All faults are limited. Faults may terminate by linking into other faults. Alternatively, the offset along a fault may diminish laterally to a pinch-out termination. Where faults pinch out, they commonly splinter into a fanning array of small segments forming a horsetail pattern (Figure 12).

The above is a description of the geometry of normal faults in plan view; however, many of the same elements of geometric complexity would be equally applicable to a cross sectional description of fault geometry. Some geometric elements of normal faults are unique to the vertical dimension because of the underlying processes involved. For example, normal faults typically steepen as they approach the surface of the earth. In theory, they should intersect the surface at a 90° angle to match the distortion of the shear-stress regime that results from that free surface, which can sustain no shear stress along it. This concave-upward geometry in the near-surface part of many normal faults results in an additional extensional stress in the rocks adjacent to the uppermost part of the fault zone that is not present at greater depth. That additional stress leads to the development of secondary structures, which may include both synthetic and antithetic faults. Thus, normal faults zones typically become simpler in their geometry with depth.

There, in fact, is a large variety of different types of secondary structures that form along normal faults that reflect a number of different processes (Figures 9 and 10). Secondary structures include Riedel shears, splays, and strain-transfer structures. Riedel shears are shear fractures typically centimeter- to meter-scale, that develop along fault zones and that are conjugate to the fault (Figure 13), but that usually have negligible displacement along them. Splays are acute-angle offshoots of a fault that are faults themselves and that probably form through a variety of mechanisms. For example, lateral changes in displacement along a fault can result in the imposition of stresses on the adjacent rocks, which can lead to the partial breakage of the fault-bounded block by formation of splay faults. In more extreme cases, splays may break over to an adjacent fault, thus forming secondary structures that transfer strain from one major fault to another (strain-transfer structures).

At Yucca Mountain, many of the secondary structures found along and adjacent to the major normal faults are associated with the fact that these faults have significant horizontal (left-oblique) components of slip, in addition to their dip slips. The oblique pattern of slip along these faults, and the associated lateral variations in percentage of extension and degree of vertical-axis rotation, throughout the Crater Flat basin, have induced geometrically complex strain patterns, resulting in an unusually messy pattern of

faulting (Figure 14). The fault zones on Yucca Mountain are both closely spaced and commonly wide in that they typically are composed of numerous anastomozing strands. In addition, the blocks between the major faults are riddled with small fault splays and strain-transfer structures between the major fault zones (Figure 11). Many of these strain-transfer features are minor pull-apart features, which reflects their relation to the strike-slip component of displacement along adjacent major fault zones.

The above characterization of the style of faulting at Yucca Mountain addresses only discrete deformation. Several types of distributed deformation are associated with faulting at Yucca Mountain, including brecciation, shearing, folding, and fracturing. Many of the faults exposed on Yucca Mountain are not discrete breaks, but rather are zones of broken rock (breccia) locally as wide as 150 m. The degree of brecciation probably is strongly a function of the abundance, weakness, and spacing of primary surfaces of weakness in the rocks, including cooling joints, gas cavities (lithophysae), and partings such as bedding as well as the size of offset and geometric complexity of the fault zone in which the breccia occur. Other things being the same, brecciation along faults should decrease with depth owing to increasing confining pressure; however, drill cores have shown that thick brecciation zones are locally present along faults even at depths significantly below the level of the potential repository at Yucca Mountain.

Shear zones are a different style of distributed breaks in which a fault is a broad zone or swarm of clustered, very minor fault strands. Shear zones can be tens of meters wide, and even where faults consist largely of discrete breaks, abundant shearing commonly is present within several tens of meters of the discrete breaks of major faults on the surface of Yucca Mountain.

Throughout the Crater Flat basin, there are abundant short-wavelength folds that have axes that parallel the strikes of the major intrabasin faults; these folds dominantly are monoclines with their axes centered on the fault zones. The major intrabasin faults generally consist of a number of strands spaced out across zones as much as 0.5 km wide. These complex fault zones may break monoclines because the mapped structural complexity may not extend below the basal Tertiary contact, and the Tertiary volcanic rocks may therefore be draped over larger, simpler fault offsets in the underlying paleozoic rocks.

Tectonic fracturing appears to be ubiquitous in the rocks of Yucca Mountain; however, the abundance of these fractures increases strongly toward fault zones. One of the major factors responsible for this fracturing is that the monoclinal folds present along most of the major faults formed at very shallow depths, where ductile folding is not possible owing to low confining pressure. The near-surface folding has been accomplished in a brittle manner, and the rocks within the zones of folding are riddled with small fractures along which there are minor displacements that together constitute the deformation that is expressed on a large scale as the folds. Because the folding extends out for 10's to even 100's of meters into the surrounding rocks around the major faults, the tectonic fracturing does the same (Lin and others, 1993).

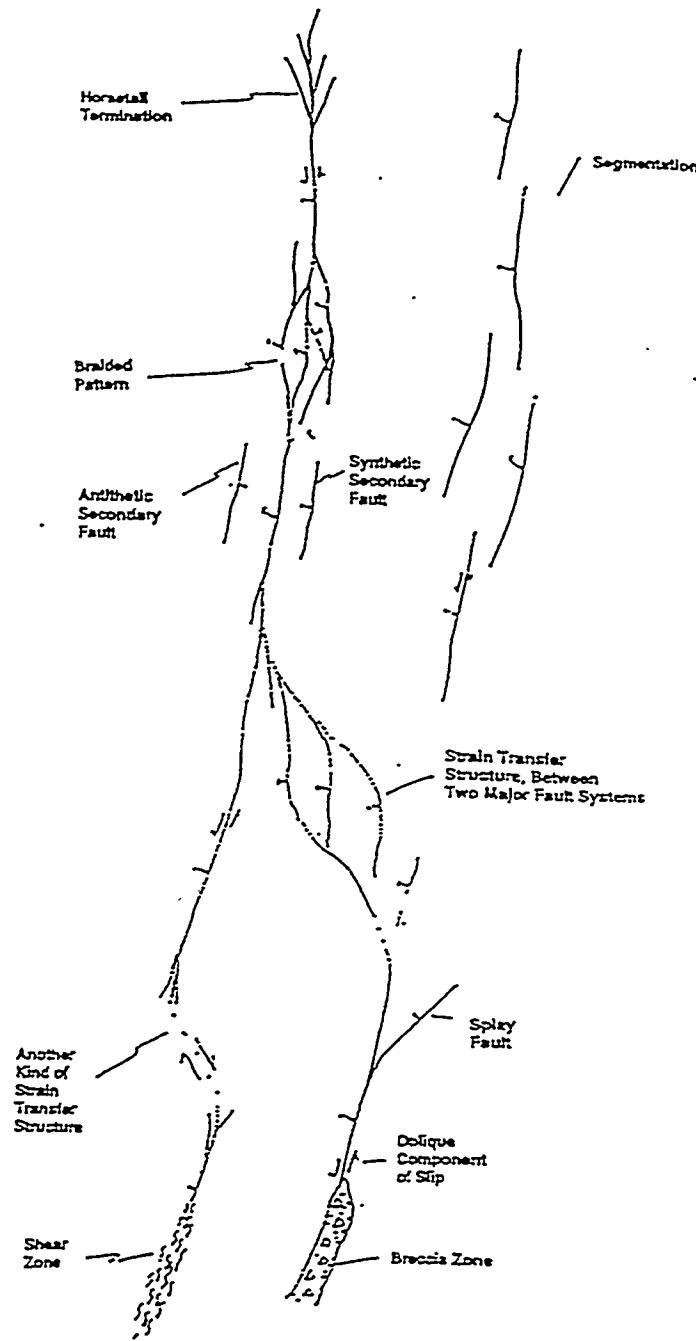


Figure 12. Plan view conceptual model of a fault zone.

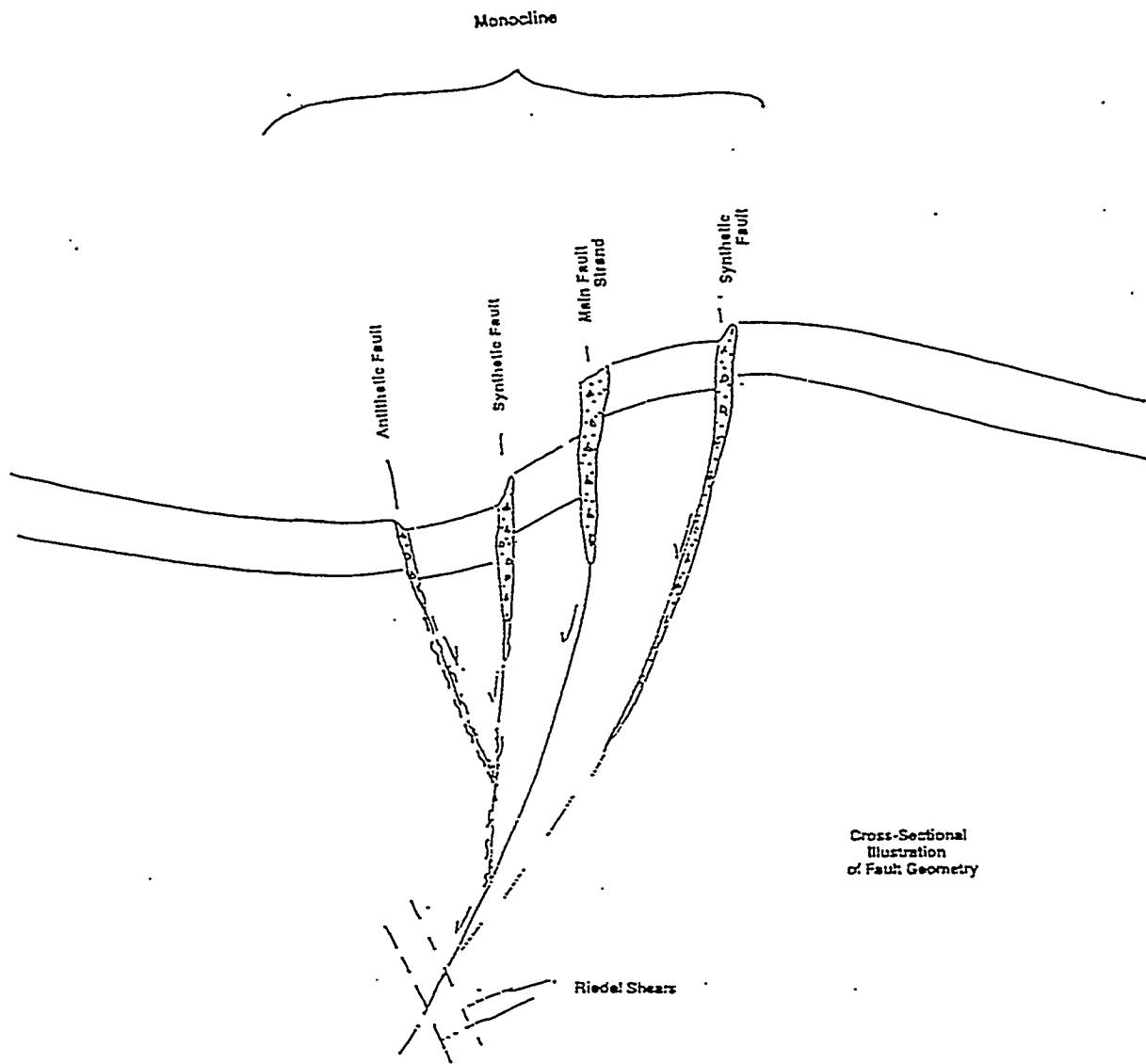
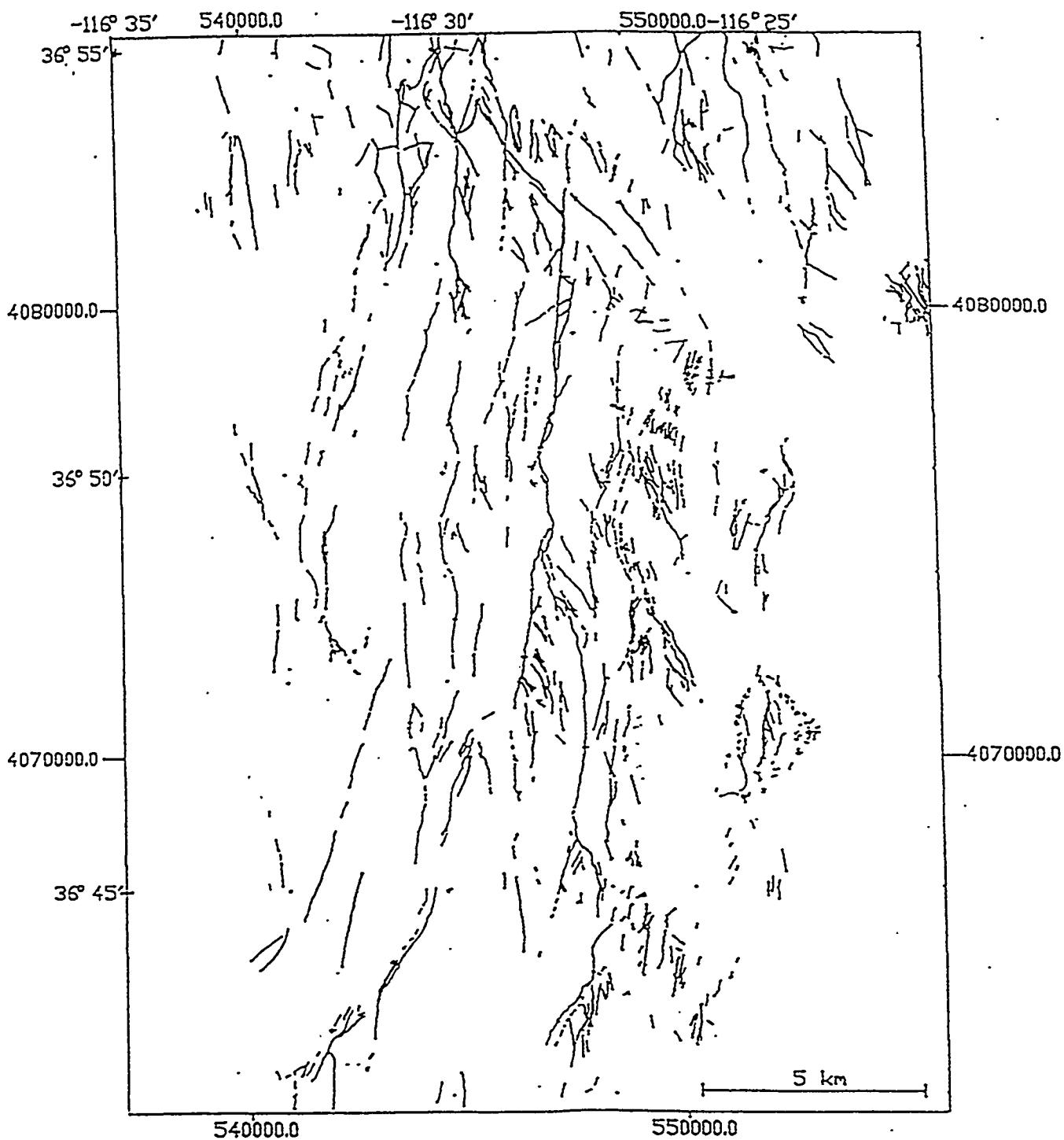


Figure 13. Cross section.



A FAULT MAP OF THE YUCCA MOUNTAIN AREA, NYE COUNTY, NEVADA
Units shown are meters (UTM zone 11) and Latitude/Longitude

Figure 14. Map of faults at Yucca Mountain.

A major cause for much of the distributed deformation along faults on Yucca Mountain is related to the manner in which faults form and evolve. When a new fault begins to form, the rocks bend until they reach a point where less energy is required to break the rock than to bend it further. The initial break commonly is very messy; numerous preexisting fractures in the rock through the zone of bending will incur displacement at first. As the fault evolves, however, typically one or a small number of traces of the fault will emerge as the most continuous and planar break(s), and this will be the weakest trace(s). Here, weakest is used in the sense that less friction is incurred by movement along these breaks than along others.

New faults would be expected to form on Yucca Mountain if there is a change in the relative orientation of the regional tectonic regime to the existing fault pattern, which could happen for two reasons: (1) the orientation of the regional tectonic regime changes periodically, and (2) the tilting and vertical-axis rotation that is occurring in the Crater Flat basin is progressively rotating the fault planes into orientations that are different from those in which they formed. Nur and others, 1986, show that, based on mechanical considerations new faults will form (in an unchanging stress regime) after 20 to 45° of rotation has occurred. For example, as a fault is tilted from an original ~60° dip down to lower angles, greater stress buildup is required to initiate renewed movement along the existing faults. Eventually, when the fault reaches a threshold dip, typically about 20°, then the stress required to reactivate the existing fault will exceed that required to form a new fault that is directly in the plane of maximum shear stress, at a dip of about 60° (Angelier, 1979; Brady and Brown, 1985; Hobbs and others, 1976). Mapping in the vicinity of Yucca Mountain by Fridrich (unpublished data) shows that the critical degree of rotation at which new faults have formed in the Yucca Mountain/Crater Flats domain is 20-25°.

The effect for vertical-axis rotation of the faults, or for an equivalent change in regional stress direction, is different than for tilting (horizontal-axis rotation). As stated above, normal faults usually form perpendicular to the least principal stress. As the strike of an existing fault changes to angles less than 90° to the least principal stress direction, the existing fault continues to be reactivated, but the resulting displacement will then be oblique slip instead of pure dip slip. Greater stress is required to initiate reactivation than when the strike of the fault is perpendicular to the least principal stress, but the increase in stress required for reactivation per given change in degree of strike is significantly less than for the fault that is tilting down to progressively lower dips. Progressive vertical-axis rotation has basically the same effect; with enough rotation, eventually less stress is required to form a new fault perpendicular to the least principal stress, than to reactivate a strongly rotated fault.

Measurements of modern stress on Yucca Mountain indicate that the least principal stress is oriented at about N55°W and is horizontal (Stock and Healey, 1988). If the orientation of stresses rotates in the future, the rotation will be initially accommodated by reactivation of existing fractures as observed for past rotations in the region (Ander, 1984). The development of new fractures will be minimized while the existing fractures are favorably orientated to accommodate the stresses. The probability is low because a significant change in stress orientation (where significant means of sufficient magnitude

to seriously affect fault behavior, i.e., formation of new faults, rather than activation of old faults) is the type of event that occurs in several hundred thousand to several million years (Zoback and others, 1981; Bellier and Zoback, 1995). Given that the major faults strike north-northeast, on average, and have dips ranging mostly between 50° and 70°, initiation of new faults appears unlikely unless there is a large change in the orientation of the regional stress. Although changes in regional stress orientation certainly occur, the probability of that happening in the next 10,000 years is very low. Hence, the probability of a new fault forming is much less than the probability a new strand or a new splay would form on an existing fault. Moreover, the formation of a new strand or a new splay is much less likely than is a simple reactivation of an existing fault strand.

Detailed Fault Studies in the Repository Area

The two dominant faults in the potential repository area at Yucca Mountain are the Ghost Dance and Solitario Canyon faults, which have been studied in three major generations of progressively more detailed work, the latest of which is ongoing (Christiansen and others, 1965; Scott and Bonk, 1984; Spengler and others; 1993, Day and others, written comm., 1995). The Ghost Dance fault is the only significant fault that cuts across the repository area. The Solitario Canyon fault zone begins at the western boundary of the repository area (Figure 11) (for current interpretation, see Day and others, 1995). Of the two, only the Solitario Canyon fault is thought to have been active in the Quaternary (Pezzopane and others, 1994; Pezzopane, written comm., 1995).

The Ghost Dance fault is about 5.5 km long and varies along its strike from a single trace to a zone comprised of several individual breaks in a zone as wide as 200 m (Spengler and others, 1993). It is a west-dipping fault, with an exposed dip of about 80°, and is everywhere a down-to-the-west normal fault. The Ghost Dance fault begins near the northern boundary of the repository area, where it is a single strand with a throw of 3 to 6 m. Near the center of the repository area, where the fault has several strands, the aggregate throw is about 30 m. Near the southern boundary of the repository area, the fault splays southward in a horsetail pattern with several individual fault strands that have an aggregate throw of about 10 m. Throughout the length of the Ghost Dance fault, the various strands of the fault cut a monocline flexure in the middle of which stratal dips are approximately flat, whereas dips on either side of the flexure are approximately 100 to the east.

About 70 m of relief are present in the site area, and it is clear from the field relations that much of the complexity of the Ghost Dance fault zone is a near-surface phenomenon; the fault zone becomes narrower and less complex with increasing structural depth of exposure. Drill-hole data (Buesch and Potter, oral comm., 1995) suggest that the throw of the Ghost Dance fault may be slightly greater at the depth of the potential repository than it is at the surface; it appears to be a growth fault within the Paintbrush Group volcanic section.

The Solitario Canyon Fault zone is a scissors fault; that is, it is a normal fault along most of its length, with strongly decreasing throw northward to a fulcrum point, north of which the fault plane continues with roughly the same strike and dip, but is then a high-angle reverse fault with a northward-increasing throw (Scott and Bonk, 1984; Fridrich and

others, in press; Sweetkind, oral comm., 1996). The fulcrum point, the point of zero throw, is about 1 km to the northwest of the northern tip of the potential repository area. From there, the throw increases southward to a value of about 300 m down-to-the-west near the southwestern margin of the repository area (Scott and Bonk, 1984). North of the potential repository area, the Solitario Canyon fault largely consists of one or a couple of strands in a narrow zone. From the fulcrum point southward, both the number of strands and the width of the fault zone progressively increase. Near the southwestern boundary of the repository area, the width of the fault zone is about 250 meters (Sweetkind, oral comm., 1996). Dips on the Solitario Canyon fault are variable, but mostly are in the range of 500 to 800 to the west for both the normal and reverse parts of the fault (Simonds and others, 1995). The monoclinal flexure associated with the Solitario Canyon fault is much more pronounced than that along the Ghost Dance fault because the Solitario Canyon fault is a much larger fault. This flexure probably extends into the westernmost part of the area currently designated for the potential repository.

Near the repository area, two major splay faults split off of the Solitario Canyon fault with northeast strikes (Scott and Bonk, 1984; Sweetkind, oral comm., 1996). The northwestern boundary of the repository was drawn to avoid the more southerly of these two splays. Both of these splays show a significant downward increase in throw within Solitario Canyon, suggesting they are growth faults in the Paintbrush Group volcanic section (Scott and Bonk, 1984; Day and others, written comm., 1995).

Estimated Fault Displacement Hazards

Studies of Quaternary displacements on the Solitario Canyon and Ghost Dance faults have concentrated on collecting data to assess fault displacement hazards for the potential repository and are part of a broader investigation of seismic risk associated with faults throughout the Crater Flat basin and the surrounding region (Pezzopane and others, written comm., 1995). The Quaternary fault data for the Crater Flat basin have shown that displacements on Yucca Mountain faults, per seismic event, are roughly proportional to fault length (Pezzopane and others, written comm., 1995). Moreover, Pezzopane and others (written comm., 1995) show that this relation between fault length and magnitude of deformation per faulting event is roughly the same as that established by Wells and Coppersmith (1994) from a worldwide compilation of data from earthquake hazard studies. Existing data at Yucca Mountain therefore provide an excellent basis upon which to forecast probable magnitudes of displacement per faulting event. Moreover, both bedrock and Quaternary studies provide descriptions of the nature of deformation that occurs along and around faults on Yucca Mountain during these events.

In a typical faulting event, Pezzopane and others (1995) estimate that the average offset on the Solitario Canyon fault has been about 0.5 meter, with a maximum offset in the central part of the fault of perhaps 1 meter. The estimates for the same two offsets for the Ghost Dance fault are 10 and 13 centimeters, respectively. The above are averages, and at a one-sigma deviation, the values would be approximately half as much on the low end and twice as much on the high end. How much distributed deformation, especially brittle folding, should be expected to accompany these discrete offsets is unclear; however, it is clear from existing fault studies, as well as theoretical considerations, that folding was a much larger factor in the early histories of these faults than it has been in the Quaternary, and is likely to be in the immediate future. In that the typical recurrence rates on these faults is 40,000 to 100,000 years for the Solitario Canyon fault, according to Pezzopane and others (1995), and longer for the Ghost Dance fault (if this fault is still active), it is unlikely that more than one faulting event will occur on either of these faults during the next 10,000 years.

Engineering Implications

The principal rock deformation occurring in a fault event is discrete offset on one or more well-defined fault traces. However, minor distributed deformation should be expected in a zone surrounding these discrete breaks, and that zone of distributed deformation may lack definite boundaries. Virtually all of the rock in Yucca Mountain has been affected to some degree by faulting-related deformation in the past and will be affected by renewed faulting deformation in the future. In defining useable area for the potential repository, it will therefore be necessary to make a decision as to how much tectonic deformation and other impacts the waste package will be designed to withstand, and the usable area under Yucca Mountain will have to be selected with that, and the past pattern of deformation in mind. Whereas new faults could form through the repository area, that is less of a concern than reactivation of existing faults because, given the feeble offset rates and low recurrence rates for faulting events on Yucca Mountain, reactivation of an existing fault strand is the only faulting event at the site that has an appreciable probability at the site over the next 10,000 years. However, fault displacement within the repository must be considered, despite its low likelihood. From the estimates of fault offset cited above, it is clear that rupturing of a container by fault displacement is not a likely event; the major engineering reasons for keeping containers out of fault zones are the threats of tunnel collapse and hydrologic effects.

A process that is more likely than faulting through the repository, however, is seismically triggered failure of the repository tunnels due to ground motion, resulting in rock falls that may rupture containers. Failure of the tunnels, by any cause, is more probable as the centers of fault zones are approached owing to the increases in fracturing as one approaches the fault zones. Rock falls induced by tectonic events are, however, less likely over the 10,000 year life of a repository than rock falls induced by other effects, such as thermal loading and mechanical relaxation of stress (Jaeger and Cook, 1979).

For an isotropic, homogeneous, unfractured rock, thermal expansion of the rock surrounding the drifts will result in compressive stresses close to the drifts and, because of the free surface at the top of the mountain, tensile stresses overhead. However, the

actual rock is fractured and has a current stress applied. Thermal expansion will generate shears on existing fractures and the effect near the drifts will be a more general stress state than simple compression or tension. Rock expansion caused by thermal loading will generate large shear stresses, resulting in failures along existing fractures; hence the actual effect of thermal loading in the vicinity of the drifts will be more complex than a simple compressive regime. The tunnels will eventually collapse, even in the case of no disturbance. Any disturbance of the stress regime in the rocks, regardless of type, will lead to strains that will weaken the rocks and joints and that therefore will accelerate the rate of tunnel collapse over the undisturbed case. In this regard, the magnitude of a disturbance is probably more important than the nature of the disturbance; the hotter the repository, the larger the thermal stresses and irreversible alteration of the rock, and the more extensive drift failure will be expected to be.

Hydrologic Implications

Fault zones may at once be preferred pathways for groundwater flow through fracture networks along their strikes and barriers to flow perpendicular to strike owing to offset-induced breaks in the continuity of permeable units or generation of gouge of low permeability. Movement along a fault could, in theory, either enhance or diminish either of these effects; however, because of generation of gouge and reduction of contact asperities, increases in permeability during a faulting event appear far more likely than decreases. The effect of water flowing through fault zones and other tectonic fracture zones probably is to decrease permeability owing to pressure solutioning of asperities that hold fractures open as well as to deposition of fracture-filling mineral deposits (Lin and Daily, 1984). Fractures through rocks composed of volcanic glass probably plug up at rates orders of magnitude higher than fractures through crystalline materials because the glass is chemically unstable. Overall, therefore, permeability along and across tectonic fracture zones, including faults, may go through a cyclic pattern of progressive fracture healing interrupted by episodic rebreaking during widely spaced tectonic events.

Displacement along a fault zone immediately within the repository area is not the only tectonic event that could change the permeability structure in the repository area. Strong ground motion can trigger displacements along minor existing fractures in a broad zone around the source of the earthquake. For example, in June 1992, two earthquakes occurred which caused short-term water-level fluctuations of as much as 90 cm in drill holes all over Yucca Mountain; these were the magnitude 7.5 Landers earthquake and the magnitude 5.6 Little Skull Mountain earthquake which emanated from sources 230 and 23 km away from Yucca Mountain, respectively (O'Brien, 1993). Whereas all of the other wells regained their original water level within several days, in one well, UE25 WT-6, the water level showed no sign of recovery at least over several months (O'Brien and others, 1995), which probably reflects permanent rock deformation in the vicinity of this well. In the next 10,000 years, magnitude 7.5 and greater earthquakes are likely to emanate from sources closer than Landers, California. Some of these earthquakes may cause significant changes in the permeability structure at and around Yucca Mountain.

Changes in water-table elevation in response to earthquakes most commonly reflect transient changes in the state of stress adjacent to the fault that moved (Muir-Wood and

King, 1993). Another possible cause of water-table change drainage of the aquifer resulting from the enhanced permeability associated with ground-motion-induced fracturing (Rojstaczer and Wolf, 1992). Between faulting events, if any change in permeability occurs along faults through the tuffs, it is most likely diminishment, due to slow, pressure-induced dissolution at asperities which hold fractures open, and much faster precipitation of minerals within fractures, especially precipitation of breakdown products from volcanic glasses. Trenching studies of Quaternary faulting on Yucca Mountain show that each new faulting event produces a large amount of new fracturing but with only trivial offset in each event (Menges and others, 1994). Hence, these events may tend to undo the effects of diminishing fault permeability between faulting events and to seldom increase the offsets responsible for most of the permeability reduction. Little evidence has been found for the formation of fault gouge at Yucca Mountain.

Thermal loading may result in accelerated breakdown of volcanic glass in the vicinity of the repository according to Wm. Glassley, LLNL. The Topopah Spring basal vitrophyre lies close enough below the repository (about 60-120m) that it may be altered to clays and zeolites. A possible consequence is the development of a perched water zone atop this altered basal vitrophyre. In one respect, tectonic events may affect repository performance because thermal loading may plug up all fractures through the basal vitrophyre of the Topopah Spring Tuff increasing the residence time for flow leaving the region below the repository. Tectonic events through Yucca Mountain could establish new flow paths through the newly-created fault zone. Tectonic fracture zones may result in a strong increase in the rate of infiltration of surface waters down to the repository. Because of the expected affects of heat around the repository, alteration of the glassy rocks is likely to cause healing of fractures through them. A faulting event during or after the thermal period could result in enhanced flow of water perched on the healed units.

In another respect, permeability enhancement may create a good connection between the tuff and carbonate aquifers, which currently are poorly connected. Today, the hydraulic gradient appears to be upward from the carbonate aquifer to the tuff aquifer (Craig and Robison, 1984). The upward hydraulic gradient is based on measurement in a single well. Indirect evidence supporting upwelling is also seen in thermal data along the Solitario Canyon and Paintbrush Canyon faults (e.g., Fridrich and others, 1994a). However, it has not been proven that this condition is present under the whole repository area. Even if it does apply to the whole repository area in the present, this upward hydraulic gradient may not be a permanent feature of the site.

5.0 DEVELOPMENT OF TECTONISM EVENT TREE

The upper Tectonic Processes event tree as seen in Figure 1 is organized by separating those processes or events operating or occurring in the repository block from those which occur outside the repository block but have an impact on the processes in the block. Two circumstances are identified as starting events within the block namely New Faults and Old Faults. Two circumstances are identified as starting events initiated outside the block: regional events coupled to the block and stress changes in the block. Changing Stress State at Repository Block addresses the possibility of regional changes in stress, e.g., by faulting, causing stress changes in the repository block. These stress changes could show up as strains which alter fracture flow or possibly alter the saturated flow system. Regional Coupling refers to fault movements away from the repository block which might be expected to affect the repository by either altering the regional flow system or by causing alteration to containers because of ground motion (e.g., rockfall damage to containers, shaking damage of contents) or to flow pathways. New faults through the repository are distinguished from old faults through the repository because no waste will be put in close proximity to recognized faults. Therefore, an old fault can not intersect waste containers and, thus, the population of containers at risk is somewhat different in the two cases.

The discussion will focus first on faults passing through the repository block. Even though this region is apparently still being extended (Levy and Christie-Blick, 1989), the current style of movement around Yucca Mountain is reported to be dip/slip (or strike/slip, which may occur as well). Since the stress regime is expected to change only slowly, based on the geologic history of this region, we presume that such movement will continue for some time. One might anticipate that some faults, new and old are, or will be, listric faults which terminate in a detachment surface resulting in a horizontal interface. Since new listric faults would appear near vertical at the surface and would have their detachment surface too deep to matter to the flow system, the possibility of such faulting producing a new fault will be ignored here. Existing shallow listric faults are another matter. There are differing interpretations of seismic data that suggest shallow curviplanar faults as a possibility. A current datum (Craig and Robison, 1984) indicates head in the carbonates is greater than in the water table aquifer, suggesting that the position of an old detachment surface relative to the carbonates is important because strike/slip (or dip/slip) movement on an old listric fault could alter connections between aquifers previously isolated from each other. Accordingly, we will not include listric faulting in discussing new faults but will preserve it in the discussion of old faults until their absence is shown by field investigations.

The repository may be hot or cold, where we define "hot" to mean that the vaporization isotherm is outside the waste container and "cold" to mean that the vaporization isotherm is inside the waste container. This distinguishes between a thermal driving source for two-phase flow and a source not able to produce vaporization. We recognize that two-phase systems are somewhat more complicated, but this definition is convenient for this report. By our definition, parts of the repository can be hot and others cold at the same

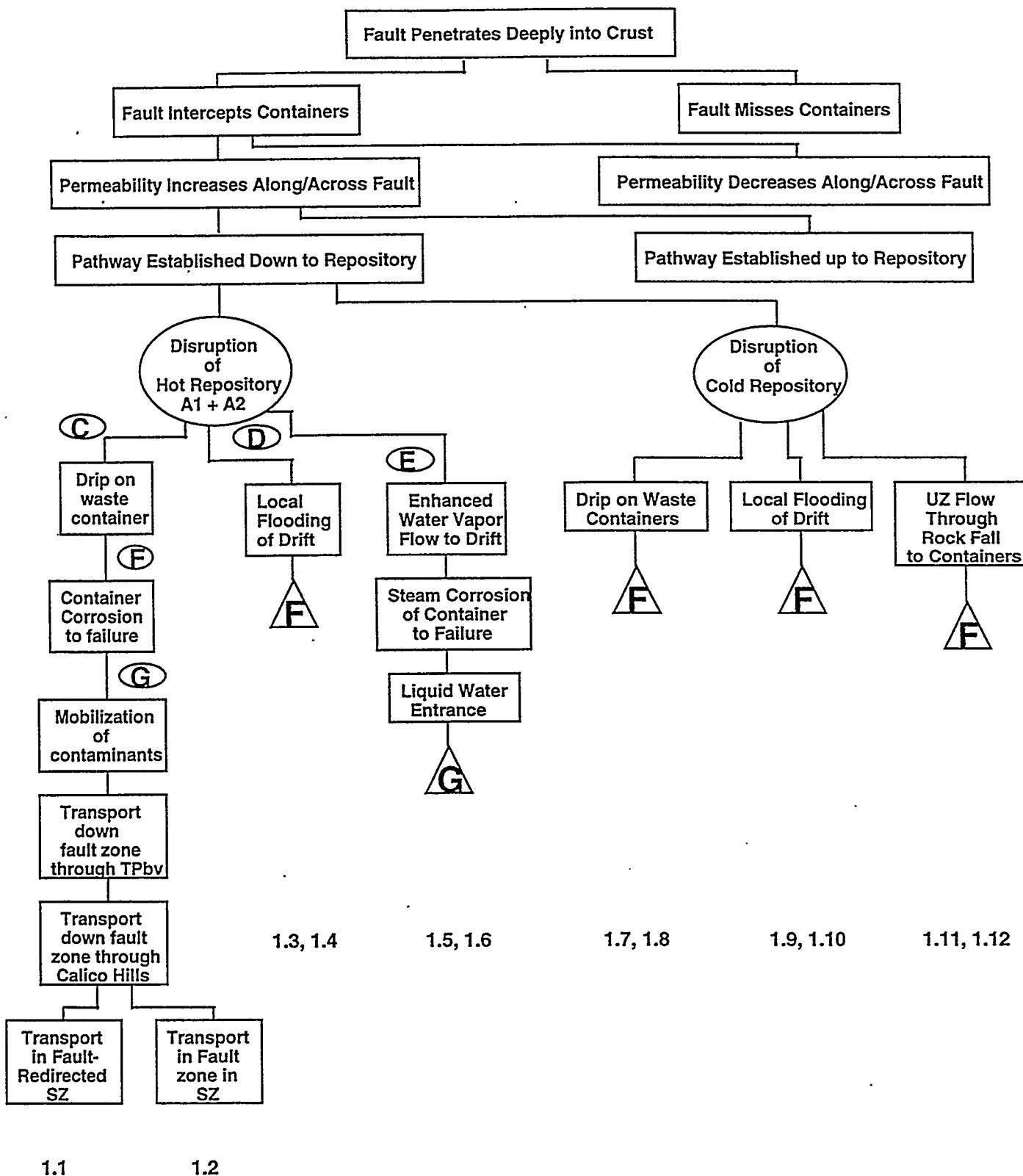


Figure 15. Tree Segment 1, Paths 1.1-1.12, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into the Crust," "Fault Intercepts Containers"...

time. The location of the vaporization isotherms will depend on repository layout and waste loading. It is not expected that 10,000 years will be sufficient time for the repository to return to the ambient rock temperature.

Cold Repository and Hot Repository are special elements of the tree and they will be discussed separately with their own sub-trees. There is a distinction between hot and cold repository based on whether the thermal output of the repository can drive significant convective flow. The reason for this separate discussion is that our interest here is how tectonic events and processes disrupt the expected behavior described in the "Nominal Flow" report (Barr and others, 1995). Our definition makes a cold repository the final state of a hot repository, a state which includes all the changes to the rock and mountain which repository heat generates. For the hot repository, we identified three different two-phase flow regimes: formation of a condensation zone or cap, formation of heat pipes, and venting from the mountain. A condensation zone is a region where water vapor generated from fluid in rock by waste container heat condenses. It may be associated with multi-phase convective circulation on the scale of a single container, a row of containers or the repository as a whole, depending on the energy and power density of the waste and the time since emplacement. A heat pipe is an engineered device that transfers heat from a heat source to a heat sink by vaporizing a working fluid at the source and condensing it at the sink. In our case, the heat source is a waste container and the working fluid is the fluid in the rock - water. The heat sink is the colder rock (below the vaporization isotherm) away from the container. Venting is the escape of vapor from the mountain. With the natural variation in rock properties, it is conceivable that all three processes will operate at some time during the hot period, either consecutively or simultaneously in different locations.

Convective circulation of fluid, either with formation of condensate zones or heat pipes, produces water-rock interactions, with solutes which have temperature dependent solubilities (e.g., silica and calcite) (Steefel and Lasaga, 1992; Casey and Sposito, 1992). Precipitation and selective dissolution are expected to alter the permeability of the rock near the drifts. Plugging of pores and fractures may occur, shutting off flow for heat pipes and limiting the return flow from a condensate cap. Further alterations are anticipated in the Topopah Spring basal vitrophyre and in the saturated zone immediately below the water table. These alterations to the flow system, formed during the period when heat is available to drive the processes, may be expected to persist or to change slowly through the life of the repository. The question to be addressed about these changes is, how might tectonic processes reasonably be expected to affect the altered region around the repository.

5.1 New Faults

A new fault could intersect containers, could provide new pathways and could alter existing pathways. It could also alter the hydrothermal flow system at the repository and is likely to cause substantial rockfall in the drifts. These possibilities are recognized in the new faults branch. Most of the FEPs in the Tectonism event tree are introduced in the “New Fault Through Repository Block” branch Tree Segment 1

Fault Penetrates Deeply into Crust

The discussion is of the section of the event tree, Tree Segment 1, shown in Figure 15, “Tectonic Processes, New Fault Through the Repository Block,” “Fault Penetrates Deeply into Crust.” “Deeply” is used to distinguish faults associated with a detachment from all others as simply as possible. We have lumped all types of faults and included the FEPs associated with them in the discussion of “Fault Penetrates Deeply Into Crust” (Figure 15). We are presuming that occurrence of these faults divides the repository block into two distinct parts and that our concern should be directed at how that division affects the saturated and unsaturated flow fields. For deep faults, we look at “Fault Intercepts Containers,” “Permeability Increases Along/Across Fault.” When the fault occurs, if there is no backfill except for the rubble from the long-term collapse of the drifts, then the waste containers can be effectively decoupled from the fault and shearing of the container rarely occurs. However, the fault will produce considerable rock fall, including stoping up along the fault. The rock fall could produce substantial damage to any containers in and around the fault zone. The fault zone is assumed more permeable than the country rock and provides a pathway allowing flow down to the repository, “Pathway Established Down to the Repository.” In this element, we have not distinguished among possible sources which feed this “Pathway Established Down to Repository.” What we mean to include is all sources, for example, infiltration from the surface and alteration or redirection of perched water flow. To continue following paths 1.1 - 1.7, we must discuss “Disruption of Hot Repository” and “Disruption of Cold Repository.”

5.1.1 Disruption of Hot Repository

The interpretation of the expected disruption is discussed in two subtrees for the hot repository and one sub-tree for the cold repository. Figure 16 is the first of these subtrees and addresses disruption of a hot repository experiencing two-phase convective flow with the formation of a condensation zone, here referred to simply as a condensation cap. Figure 16 shows four choices for the size and distribution of the condensate zone: over single containers, over single panels, over adjacent panels and over the entire repository. Current conduction calculations modeling individual containers and rows of containers (as smeared sources) and honoring repository layout suggest that the vaporization isotherm, which controls the location of the condensation zone, will have considerable structure (Ryder and Dunn, 1995). This structure is important for the modeling of shedding of condensate from one drift to another or for shedding from one part of a single

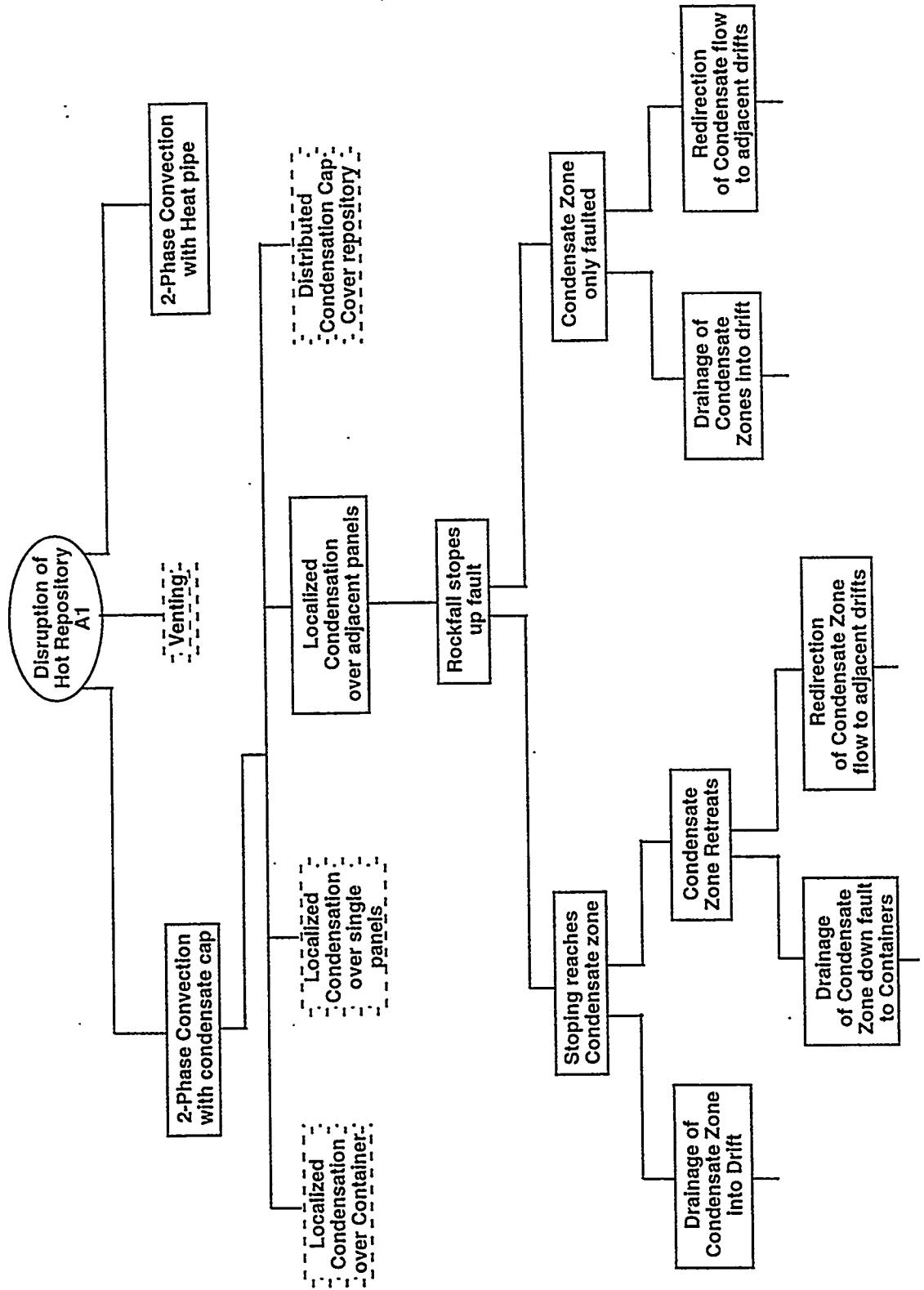


Figure 16. Tree Segment A1, "Disruption of Hot Repository, " "Condensate Zone" ...

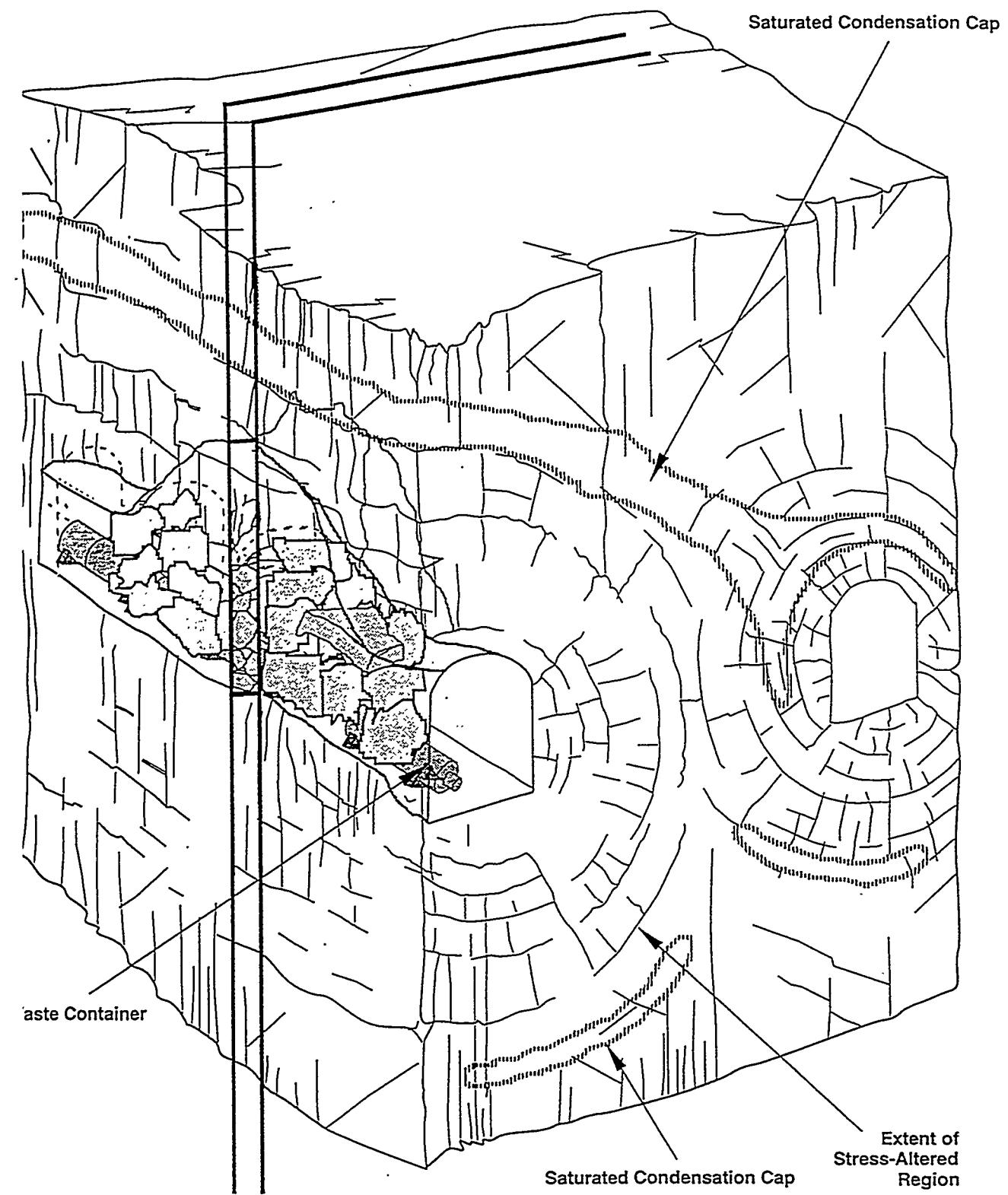


Figure 17. Conceptual drawing of stoping up the fault to reach the condensate zone.

drift to itself. Which of the four choices is the correct description will depend on thermal loading, that is, power density, the waste stream and the time after loading. Based on the conduction calculations we selected “Localized Condensation over Adjacent Panels” for continued discussion. The arguments are similar for the other branches. The tree continues with the response to the through-going fault, “Rockfall Stopes Up Fault” (Figure 16).

Figure 17 shows a possible interpretation of how a fault intersects the repository and stoping drops rock onto the waste containers. Here the stoping reaches the condensate zone.

The tree separates “Stoping Reaches Condensate Zone” from “Condensate Zone Only Faulted” because the consequences are somewhat different. The “Condensate Zone Only Faulted” branch allows for “Drainage of Condensate Zone into the Drift” presumably down the fault zone, and for “Redirection of the Condensate Flow to Adjacent Drifts” (or elsewhere in the same drift). The “Stoping Reaches Condensate Zone” branch considers “Drainage of Condensate into Drift” and “Condensate Zone Retreats.” In the latter case, which is accompanied by movement of the vaporization isotherm further away into the rock, the intent is describe a newly formed condensate zone which locally supports higher gradients for redirecting flow into adjacent drifts.

Each of the branches of the sub-tree then reconnects with Tree Segment 1 as indicated. The disruption has locally altered the amount of fluid moving to the drift and its mode of movement. One should note, however, that some effects, like possible flooding and increased humidity, extend to all containers sharing a drift - a common mode failure. Figure 18 is a sub-tree displaying the corresponding hot repository for the case that heat pipes have developed around the waste. Here the choice is between ‘Heat pipes at Multiple Containers’ and ‘Heat Pipe at Single Containers.’ We identify two differing long term possible behaviors of heat pipes: ‘Continuing Heat Pipe’ and ‘Evolving Heat Pipe.’ A ‘Continuing Heat Pipe’ is one where the water-rock interactions never succeed in shutting off the circulation necessary to support the hydrothermal flow necessary to maintain the heat pipe. Eventually this heat pipe becomes extinct because its thermal output is no longer able to drive the flow system. An ‘Evolving Heat Pipe’ is one the water-rock interactions eventually plug the pores and fractures, shutting off the circulation necessary to have a heat pipe. Figure 19 shows a fault intersecting a drift where heat pipes are active. The sub-tree then reconnects with Tree Segment 1, as indicated.

The branch “Venting” is not discussed in detail. If venting already occurs then increasing permeability does not allow more. It then is the rock fall in the drifts, particularly in the fault zone, which is the issue, because crushing and rupturing of intact containers allows gaseous contaminants (e.g., $^{14}\text{CO}_2$) to escape more rapidly than might be anticipated from a corrosion model of the waste containers. Such analysis proceeds from consideration of the distribution functions for faulting and container damage as a function of rock fall and does not seem to require development of a more detailed scenario.

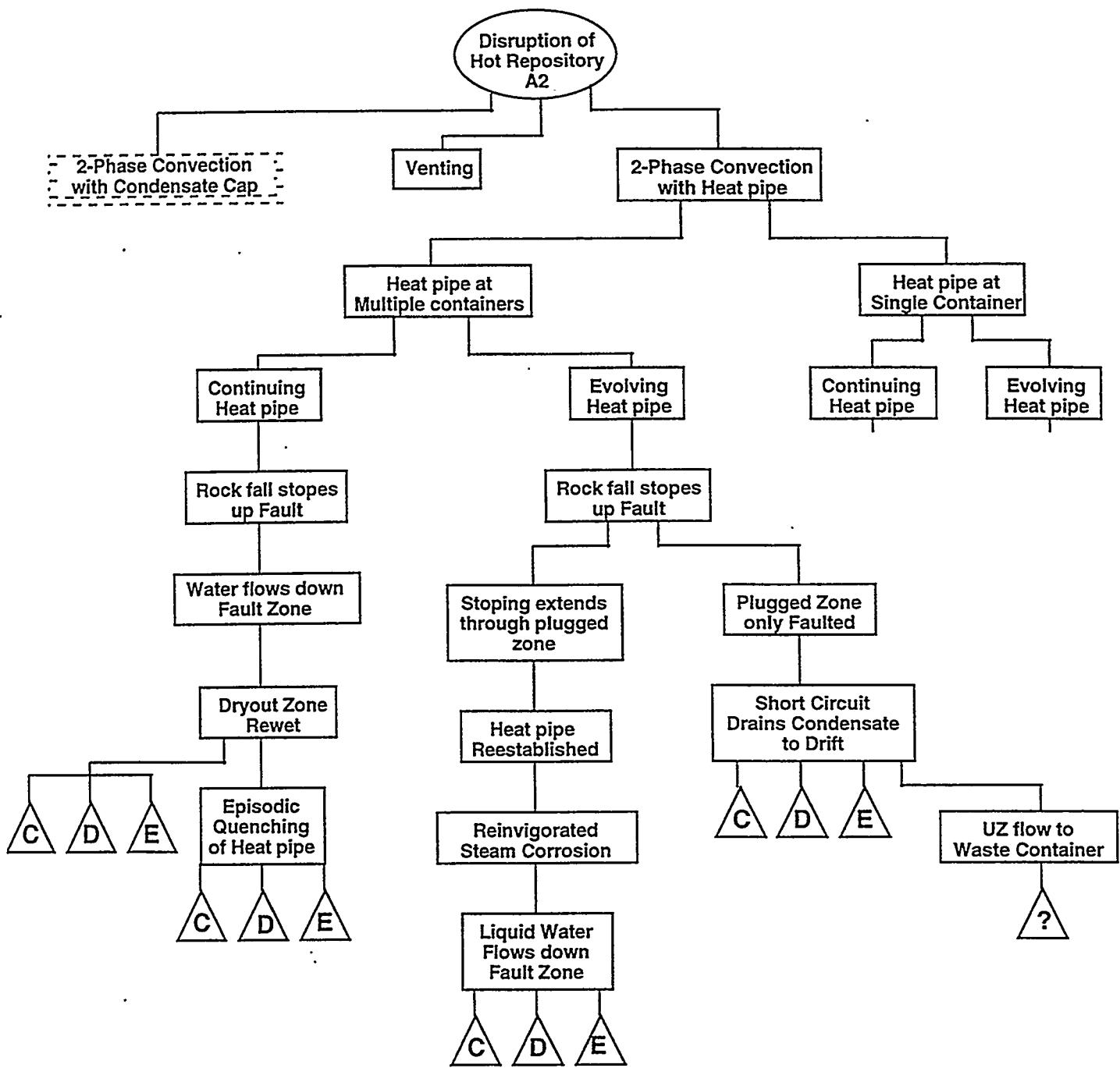


Figure 18. Tree Segment A2, “Disruption of Hot Repository,” “Heat Pipes”...

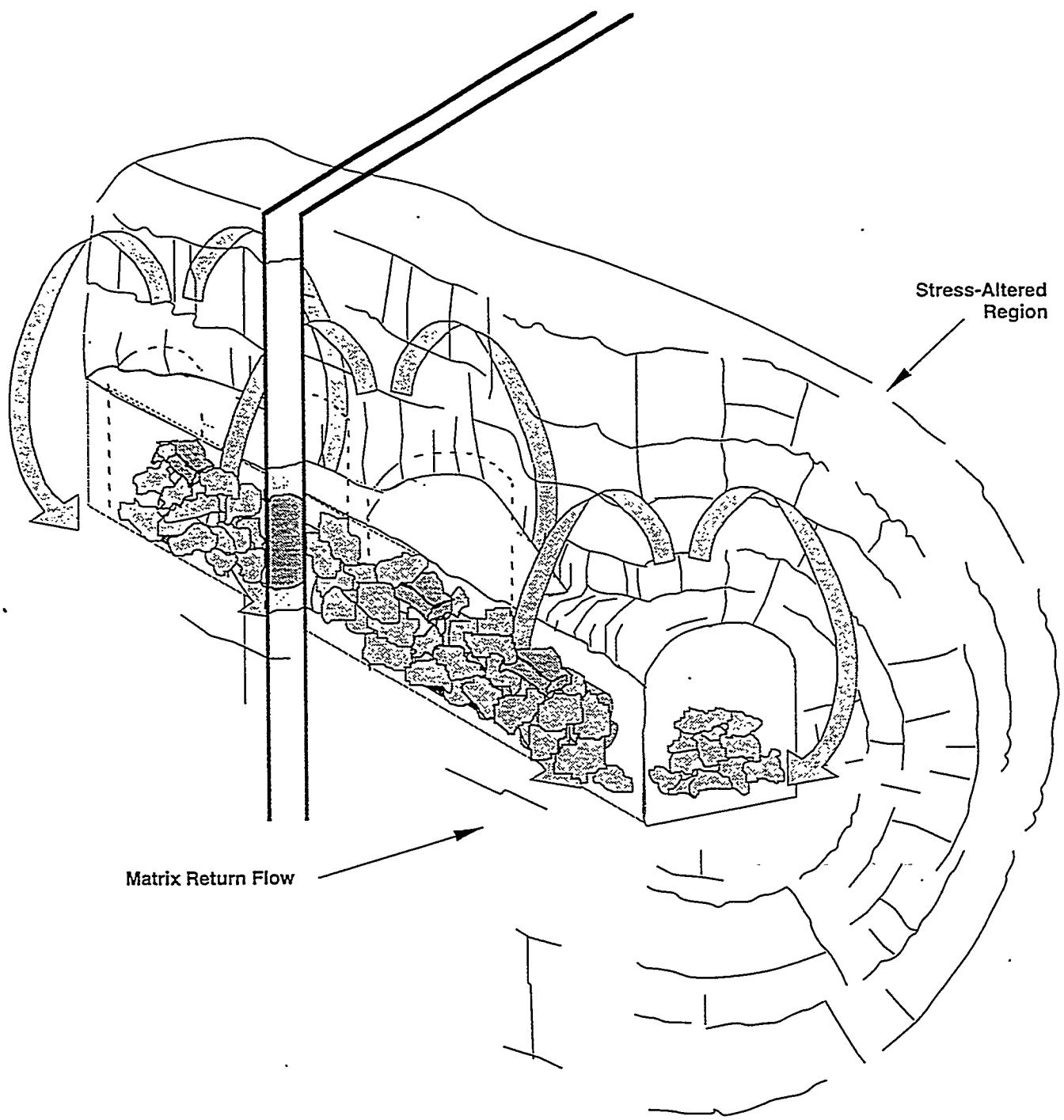


Figure 19. Conceptual drawing of stoping up the fault at a drift with heat pipes.

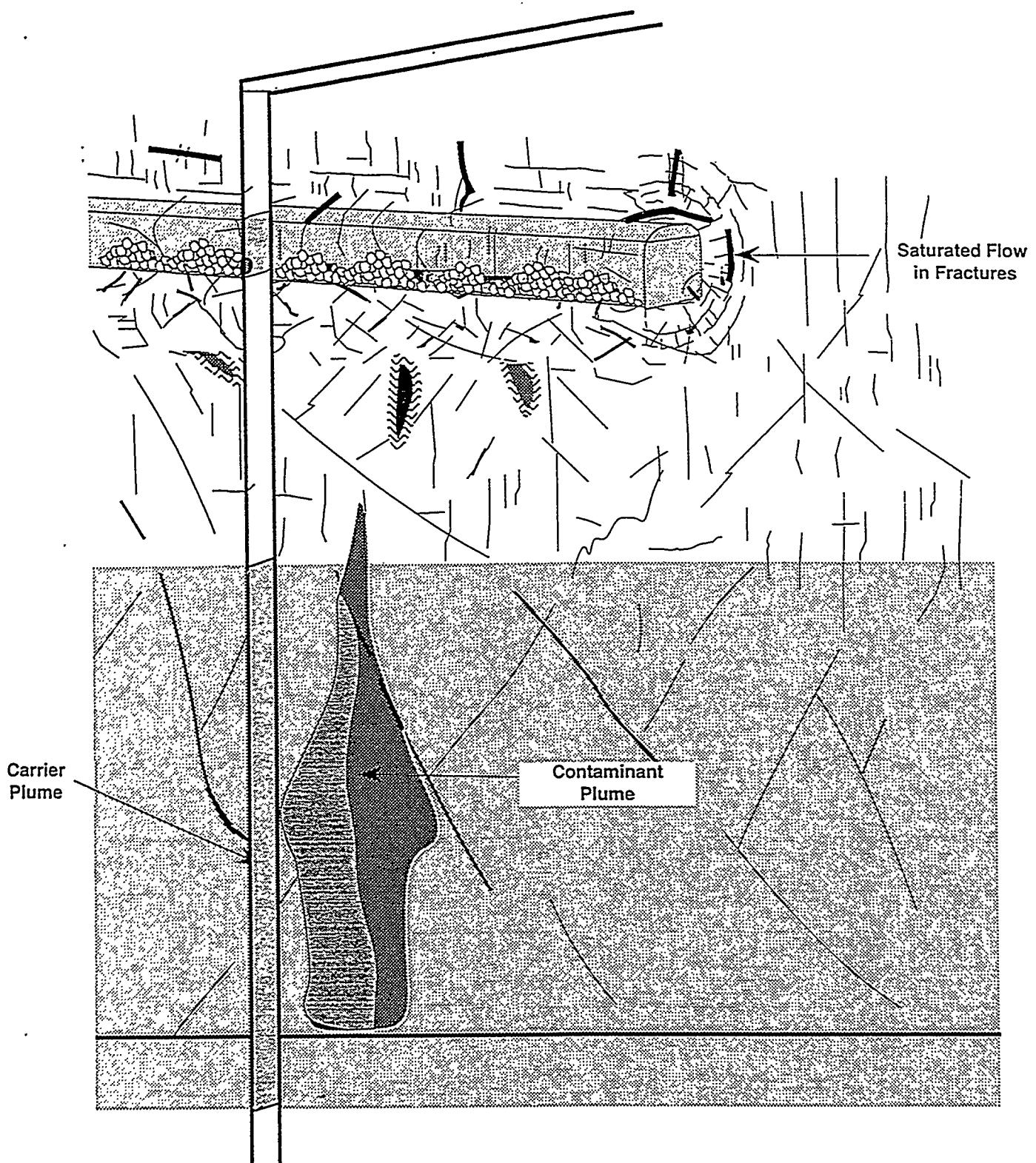


Figure 20. Conceptual drawing of transport down the fault through the Topopah Spring basal vitrophyre.

Continuation of Tree Segment 1

Paths 1.1-1.6

Paths 1.1 -1.6 below “Disruption of Hot Repository” continue by considering three different consequences for water being supplied due to the disruption: “Drip on Waste Container,” “Local Flooding of Drift” and “Enhanced Water Vapor Flow to Drift.” This branching is based on the flow rate of water, as controlled by the disruption, arriving at the waste container. The first, “Drip on Waste Container,” is presumed to suffice to cause local aqueous corrosion of the container (“Container Corrosion to Failure”). For the purposes of this report, a failed container is one which allows unimpeded access to the waste and its exit to the drift. The flow rate must be adequate to ensure enough local chilling of the waste so that “Mobilization of Contaminants” can occur. This chilling is controlled by the temperature and therefore the age of the waste, the presence or absence of backfill and any chemical effects of the remains or residue of the container. If liquid water can not exist in this environment, there can be no mobilization of contaminants (gaseous components are not considered here). The mobilization can be in the form of solutes, colloids, or both. The distribution function describing partitioning of the contaminants between solute and colloids is assumed to be known from experiments. Paths 1.1,1.2 continue with the element “Transport Down Fault Zone Through Topopah Spring Basal Vitrophyre.” The TPbv is specifically mentioned because it is possible that the basal vitrophyre has been chemically modified by heat and moisture during the hot period of the repository. Those modifications are expected to include alteration to clays and zeolites and possible welding of fractures. The fault zone generates a pathway through the altered Topopah Spring basal vitrophyre which does not exist in the undisrupted flow system. It is likely that the residence time for contaminants in this new pathway, differs from that of old pathways.

The tree continues with “Transport Down Fault Zone Through Calico Hills Units” (Figure 20). The argument for considering this element is like that for the TPbv, a new set of pathways has been created in a different rock unit. Path 1.1 concludes with “Transport in Fault Redirected Saturated Zone,” meaning that transport is in a water table aquifer for which the flow properties, direction of flow and gradient, have been altered by the faulting. Path 1.2 concludes with “Transport in Fault Zone in Saturated Zone,” which presumes that transport is more or less confined to the newly created fault zone where ever that reaches the accessible environment.

Paths 1.3.1.4 beneath “Disruption of Hot Repository” consider the case that flow of water to the drifts as a result of the faulting is sufficient to cause “Local Flooding of Drift.” Although the faulting may provide paths for enhanced water flow both to and from the drift (resulting in no net change in water contact with the waste packages), there are other factors that may cause flooding. For example, the drift bottom may have the invert (concrete segments or possibly rock ballast) still in place and any buckling in the floor could be filled by overflow from inflow; the strain does not have to be homogeneous across the drift, so the exit cracks could have a different transmissivity from the entrance cracks. The flow must be such that waste container heat is inadequate to drive away the water. The volumetric rate of flow required is dependent on the thermal output of the containers at the time of faulting. All the waste containers in a drift being locally flooded

are exposed to enhanced corrosion and more than a single container may be compromised in this single-mode failure. The remainder of paths 1.3 and 1.4 parallel paths 1.1 and 1.2 with the amount of water being the principal change.

Paths 1.5 and 1.6 beneath "Disruption of Hot Repository" refer to a more progressive alteration of flow into the drift, starting with "Enhanced Water Vapor Flow to Drift" from the disruption and proceeding to "Steam Corrosion to Failure" before enough water has entered to allow mobilization of contaminants ("Liquid Water Entrance"). The paths continue as the case of paths 1.1, 1.2 with the difference being in any possible differences in the chemistry of contaminants mobilized under the two different circumstances.

We now return to "Pathway Established Down to Repository" to consider the case of "Disruption of a Cold Repository."

5.1.2 Disruption of Cold Repository

Figure 21 develops the sub-tree for disruption of a cold repository. A cold repository is the eventual state of a hot repository. By the definition used in this report, a "cold repository" is one in which the vaporization isotherm is inside the container. The vaporization isotherm could have reached far into the rock during the hot period and eventually returned, leaving chemical alteration of the porosities due to water-rock interactions and mineralogical phase changes in its wake. This excursion has included thermal expansion of the rock and produced zones of compression and tension around the drifts (Jung and others, 1994). As the repository reaches the cold state, surrounding rock relaxes into the drifts, gradually filling them with rock fall. When faulting occurs, further rock fall is produced, particularly along the fault zone. "Rockfall Stopes up the Fault," possibly damaging intact waste containers and rupturing and crushing corroded containers. The sub-tree continues with two branches, "Stoping Extends Past Altered Zone" and "Altered Zone Only Faulted." These branches recognize that the zone of hydrothermal alteration driven by the hot repository is of limited extent. The "Stoping Extends Past Altered Zone" is to consider that a substantial connection of the drift to a more productive region of flow past the altered zone may occur. This connection produces two branches, "Saturated Flow Drainage to Drift" and "Unsaturated Flow to Drift Reestablished." The latter branch recognizes that the rock fall of the fault zone may provide good contact and a good flow path with the remains of the waste container. The branch "Altered Zone Only Faulted" covers the possibility that stoping in the fault zone does not extend through the altered zone. Flow would then still have to traverse a region with plugged pores and fractures. The tree branches to "Saturated Flow Drains Down Fault" and "Unsaturated Flow Lateral Diversion Impeded" which describe two possible different flow modes with differing volume constraints. The former represents the conceptually idealized flow down a fault while the latter tries to account for the possibility that if there is lateral, down-dip unsaturated flow in the rock, an impediment to flow like a fault could produce local saturation in the rock next to the fault with increased flow to the drift. Each of the branches then connect to Tree Segment 1 as indicated.

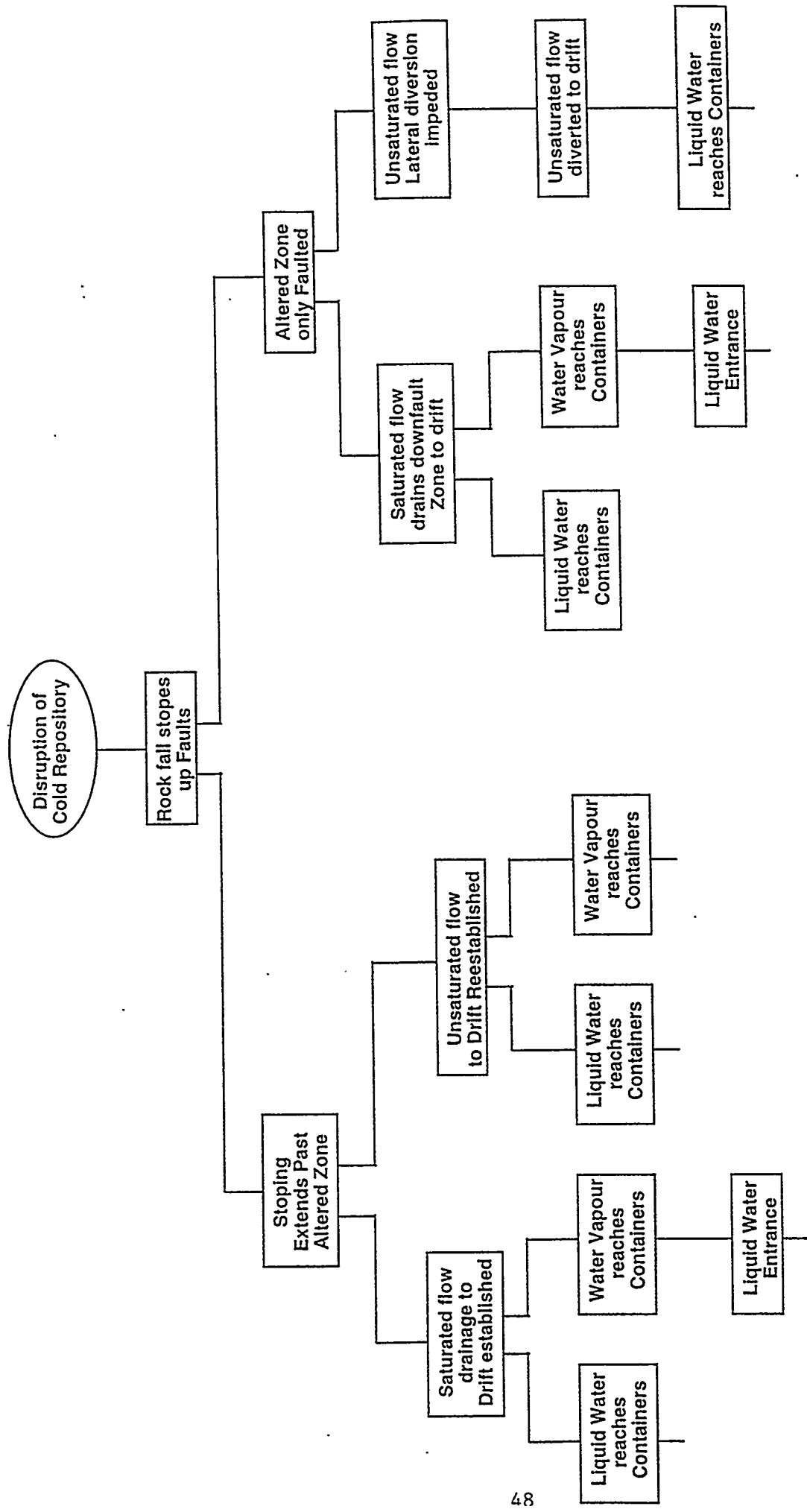


Figure 21. Tree Segment, "Disruption of Cold Repository"...

Continuation of Tree Segment 1

Paths 1.7-1.11

Paths 1.7 and 1.8 involve fluid reaching the waste containers to "Drip on Containers." Unlike the case for the hot repository where a minimum flow rate as a function of temperature is required for liquid to persist on the containers, here any amount will do. This drip results in "Container Corrosion to Failure," "Mobilization of Contaminants" and continues as did the corresponding branches for the hot repository. Presumably, the temperature difference between hot and cold can produce different speciation of solutes for transport and a different distribution between colloids and solute, so that, even though the words appear the same the actual implications may differ. Similarly, the branch paths 1.9 and 1.10, follow the discussion for the hot repository absent the requirements on minimum flow rates and the arguments will not be repeated.

The last branch for the cold repository, path 1.11, starts with "Unsaturated Zone Flow Through Rock fall to Containers." In the hot repository, this branch was not possible because of the location of the vaporization isotherm and the small flow rate. When the flow rate is not constrained in this way, unsaturated flow can reach the waste containers. The branch continues with "Container Corrosion to Failure," where unsaturated flow supplies the water for corrosion, and "Unsaturated Mobilization of Contaminants" where the unsaturated flow system determines how the contaminants are mobilized. We assume that speciation and the distribution between solutes and colloids may be different than for saturated flow, but experimental work is required.

If the fault zone is "dry," then the flow condition is one of non-saturation. If the flow is unsaturated, the plume of contaminants can not enter the fracture and, thus, must work its way around the fault zone and through the Topopah Spring and Calico Hills units to reach the water table ("Transport Around Fault Zone Through the Tpbv," "Transport Around Fault Zone Through Calico Hills"). On reaching the water table it is expected that the contaminants will simply be "Transported in the Saturated Zone." The only unique feature is that the carrier plume transporting the contaminants may be well localized because of the fault zone and may be a point source or a series of point sources along the fault zone. The term carrier plume is used to describe the localized flow field that is established through and below the drifts, to which contaminants are added. This carrier plume carries the signature of the repository (temperature, pH, dissolved Fe, etc.).

Tree Segment 2

We now go back up the tree to "Permeability Increase Along/Across Fault" to consider an alternative to "Pathway Established Down to Repository," namely "Pathway Established Up to Repository" (Figure 22).

"Pathway Established Up to Repository," is intended to describe the behavior of a fault which can act as a conduit bringing fluids to the waste as well as transporting contaminants away.

How a hot repository may be disrupted by a fault has just been discussed, so that discussion will not be repeated. Three possible driving forces are identified to bring water up from below: existing heads in the carbonate aquifers (or unknown lower systems) drive fluids to the repository, "Seismic Pumping" and "Regional Alteration of the Saturated Zone Flow System." We will consider the case of "Head Driven Flow Up From Carbonates to Repository" first. This case requires that the heads in the carbonate or lower units, which are connected to the repository by the new fault zone, be 200 or more meters greater than those in the overlying tuff aquifer. The only datum in this vicinity in the carbonates shows a head difference of 20m (Craig and Robison, 1984). Further, the deduced flow direction for the carbonate aquifers makes it unlikely that the head difference will be much higher, to say nothing of more than 200 m higher. However, since we can not exclude the possibility on the basis of a datum, to be complete we will consider the consequences.

In the elaboration of the hot repository, there were changes to the hydrothermal flow system because of rock fall. Those changes altered the influx of fluid, principally from above. Rock fall still occurs and alters flow into the drift. Path 2.1 tracks the influx coming up from the carbonates and causing early and possibly extensive "Two-Phase Rewetting of the Dryout Zone." The influx provides "Liquid Water Corrosion of Containers" and "Mobilization of Contaminants." This water brought up from below has a different temperature and chemistry than water in the flow system around the repository or in the tuff aquifer (water-table aquifer). The branch continues with "Transport in Drifts Away From Fault Zone," that is, water entering from below moves down the drift away from the fault zone to exit into the flow system elsewhere and presents a common mode failure for containers in the drift. The fluids, carrying contaminants, are "Transported in the Flow System Through the Topopah Spring Basal Vitrophrye" and "Transported Through the Calico Hills" in the existing, non-faulted flow system. Contaminants then enter the tuff aquifer and are "Transported in the Fault-Redirected Saturated Zone," where we have presumed that heads now connected to the saturated zone below the repository sufficient to raise water 200 or more meters will, in fact, significantly redirect the saturated zone flow system.

Path 2.2 branches from path 2.1 after "Transport in Drifts Away From Fault" with "Transport to Outfalls." Flow which reaches the repository may be able to reach natural outfalls like springs or seeps located below the base level of the repository away from the mountain.

Paths 2.3 and 2.4 follow path 2.1 down to "Mobilization of Contaminants" and then branch to allow for "Transport Down the Fault Zone Through Topopah Spring Basal Vitrophyre" and "Transport Down Fault Zone Through the Calico Hills." The idea is to allow for a more intricate but less likely plumbing being established in a fault zone, with part of the zone supplying a connection to the carbonates and below and part of the zone connecting to the water table. A possible example which has been suggested is dip/slip (or strike/slip) movement establishing several faults parallel to but displaced from an existing fault. Paths 2.3 and 2.4 then split as shown to allow for "Transport in Fault Redirected Saturated Zone" and "Transport in Fault Zone in Saturated Zone" respectively.

Paths 2.5, 2.6, 2.7, 2.8 address the circumstance that the flow up is so large that waste containers are quenched, "Quenching of Hot Containers." That is, the containers are cooled below the vaporization temperature and maintained there for the duration of the upward flow. The remainder of the paths are similar to paths 2.1, 2.2, 2.3, and 2.4 respectively and the discussion won't be reiterated.

Returning to "Disruption of Hot Repository" (Figure 23), the branch, Tree Segment 23, paths 2.9-2.12, starting "Seismic Pumping" offers an alternative means for forcing water up to the repository from below. This element refers to movement of water driven by stresses established in the rock by the earthquake (and fault), which are, in part, relieved by movement of water, that is, relief of pore pressure from zones of compression to zones of tension. This phenomenon has been discussed extensively by Sibson (Sibson, 1987; Sibson and others, 1988) and is often referred to as Sibson pumping. Interpretations of current data do not support seismic pumping as a credible mechanism to threaten the repository (DOE, 1995; National Research Council, 1992). Initial analysis of seismic pumping for earthquakes beneath Yucca Mountain indicate that the mechanism is unable to move water to the repository except, perhaps, in a few fractures which drain almost as fast as they fill (Carrigan and others, 1991). According to B. Arnold, SNL, more detailed analyses of seismic pumping have been done with consideration of the fact that current movement on the faults in this region is dip/ slip (or possibly strike/ slip). Results are to be reported in the next year or so (Arnold, 1996). Branches 2.9-2.12 below "Seismic Pumping" are similar to those of paths 2.1-2.4, respectively.

Tree Segment 3

The last set of branches, Tree Segment 3 (Figure 23), paths 3.1-3.4, are driven by changes produced by the fault in the saturated zone flow system. This branch begins below "Disruption of Hot Repository" with the element "Regional Alteration of Saturated Zone Flow" (Figure 23). We have in mind more extensive alteration to the saturated zone than was discussed in earlier scenarios, namely that the location of the water table rises under the repository. Two cases are distinguished: "Water-Table Rise," and "Water-Table Rise to Repository" (Figure 24). For the first case, path 3.1, "Water Table Rise" the distance from the water table to the repository has been reduced. This is followed by "Two-Phase Rewetting" to include the possibility that the water table is now close enough to the repository to participate in the two-phase hydrothermal flow systems, either the heat pipe or condensation zone systems. In this case, the water table then can act both as a condenser and as an infinite water source, changing the amount of water circulating through the repository region.

Unlike the situation for flow up a fault zone, this water source could be available under the entire repository. The Calico Hills units and their associated zeolites are now no longer in the flow path, because the Calico Hills units are well below the water table.

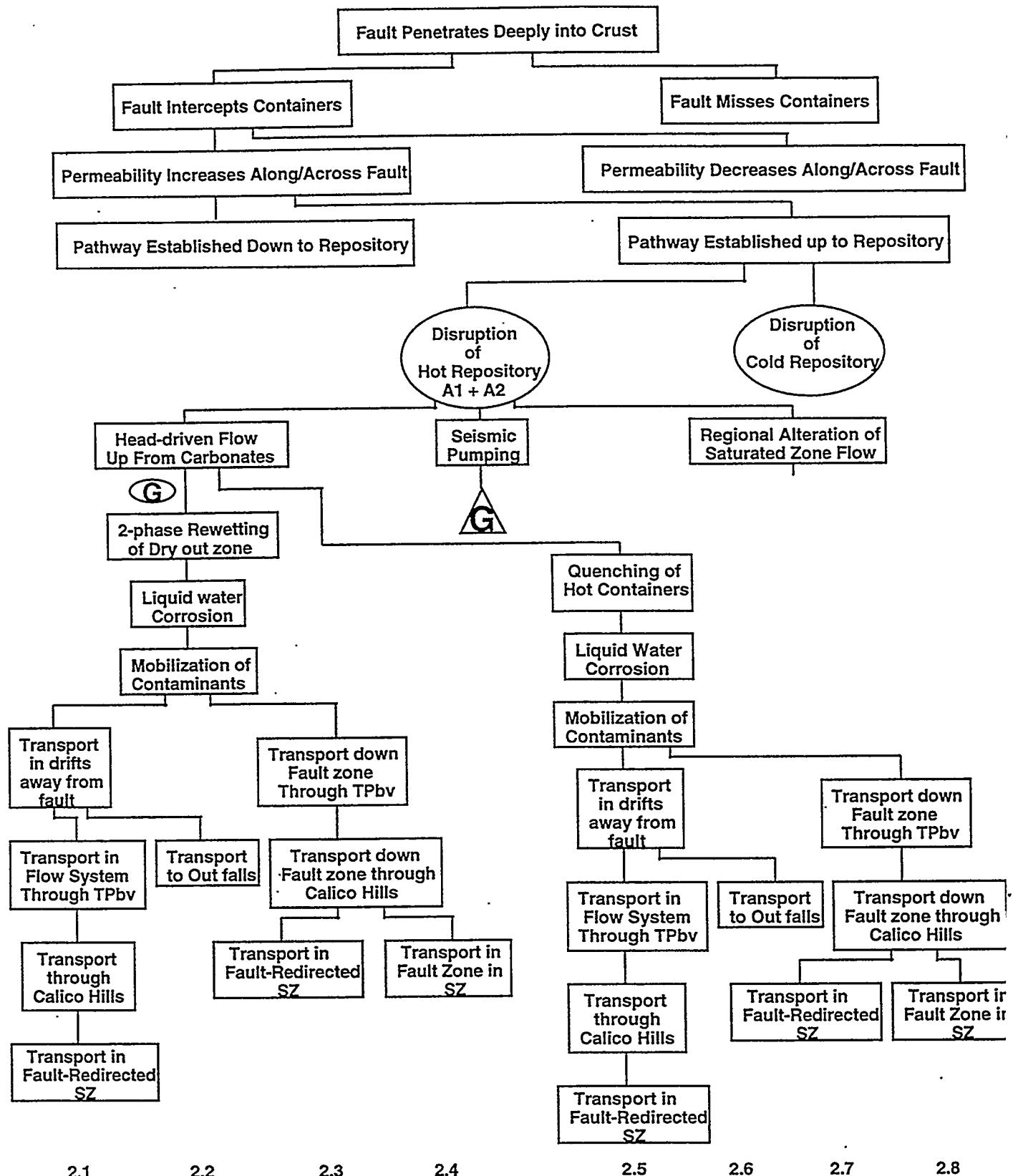


Figure 22. Tree Segment 2, Paths 2.1-2.8, "Tectonic Processes," "New Fault", "Fault Penetrates Deeply into the Crust", "Fault Intercepts Containers", ...

The branch continues with "Vapor Corrosion of the Containers" and "Mobilization of Contaminants." Contaminants can be mobilized in the unsaturated flow system since rock fall has presumably established a flow path to and from the waste containers ("Transport in the UZ Flow System"). The rise of water table allows the possibility that new outfalls, springs and seeps, are now active and flow is increased to old ones. The release mode of this path, including both new outfalls and alteration of flow to old outfalls will be summarized as "Transport to New Outfalls."

Path 3.2 follows path 3.1 to "Mobilization of Contaminants," where it is assumed that the mobilization is in saturated flow. The transport then becomes "Transport Down the Fault Zone" to the new water table and release occurs by "Transport to New Outfalls."

Returning to "Regional Alteration of Saturated Zone Flow" we now consider the alternative location for the new water table, "Water Table Rise Through Repository." The water table has been elevated to or above the repository horizon so the repository is now flooded. We will presume that the entire repository is affected, even though one could imagine circumstances for the location of the fault zone for which only part is under water. Two branches will be discussed, "Quenching of Hot Containers" and "Formation of Saturated Zone Convective Cell." These branches distinguish early flooding of the repository when the heating is likely to produce the most vigorous circulation from later in the hot period when such flow is not possible or is only possible locally. Path 3.3 continues below "Quenching ..." with "Liquid Corrosion of Containers" and saturated "Mobilization of Contaminants" as would be expected. It concludes with "Transport to New Outfalls."

There seem to be no paleo-springs identified at Yucca Mountain, within the potential repository area, that could be associated with such a high water table (DOE, 1995, sec. 3.1.2.2.7) - it apparently has never occurred at the proposed repository site and could be considered physically possible only because of existing high heads to the north of the site.

Path 3.4 describes development of large-scale convection in the new saturated zone, "Formation of Saturated Zone Convection Cell." Such convective flow has been considered in the past (e.g., Hunter and others, 1983) for hot repositories located below the water table and there is work on the scale of movement, velocities and volumes, available. The continuation is "Liquid Water Corrosion," Saturated Flow Mobilization" and "Transport to New Outfalls."

Tree Segment 4

We now turn to the alternative to a hot repository for "Pathway Established Up to Repository," namely "Disruption of a Cold Repository" (Figure 25). As with the hot repository the first branch considered is "Head Driven Flow Up From Carbonates." In the cold repository, by definition, there is no two-phase flow; however, cold does not imply that the temperature is the prewaste emplacement temperature of the rock. Because the temperature of water from depth is likely to be colder than waste containers in this

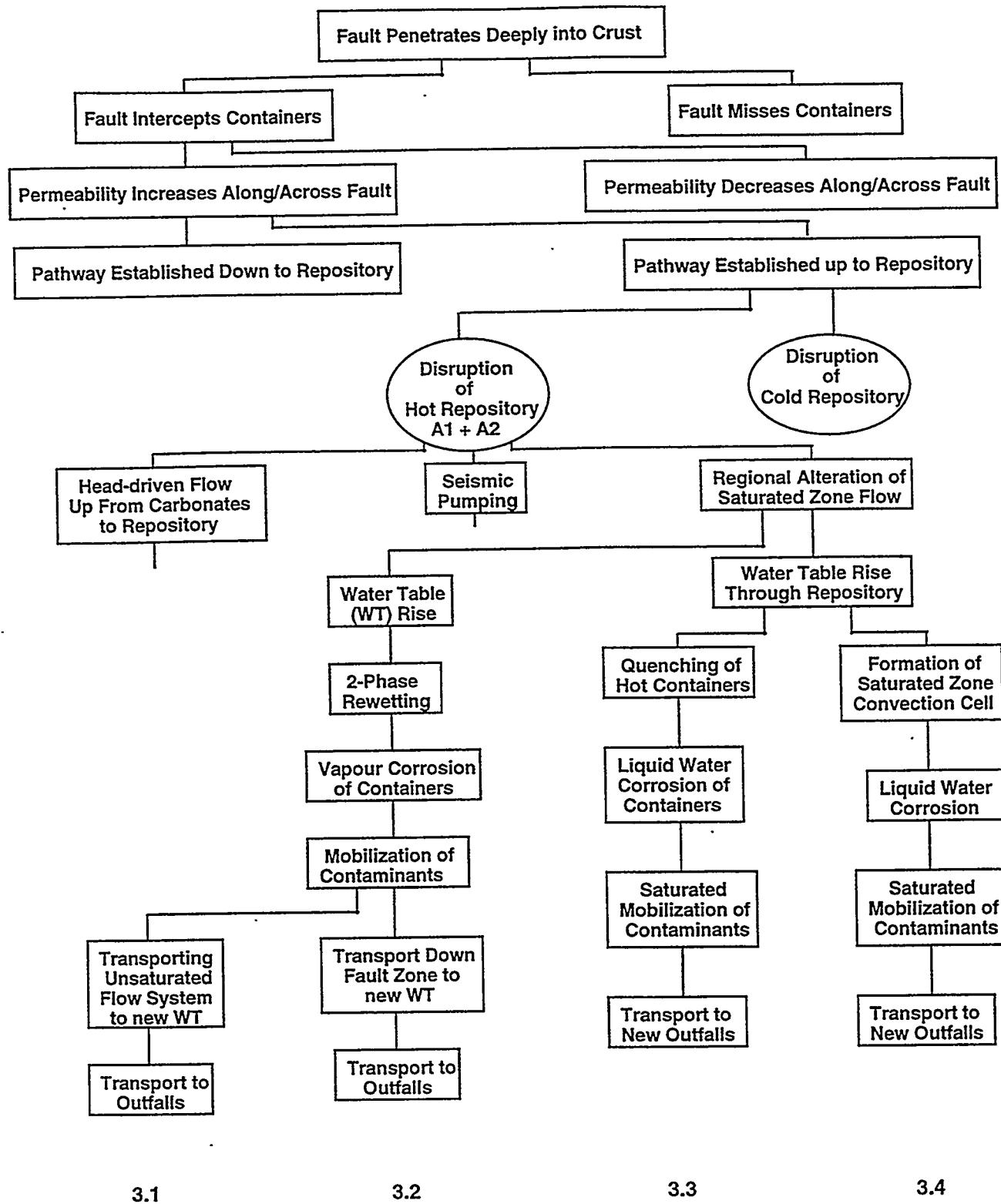


Figure 23. Tree Segment 3, Paths 3.1-3.4, "Tectonic Process, ""New Fault," "Fault Penetrates Deeply into Crust," "Fault Intercepts Containers," ...

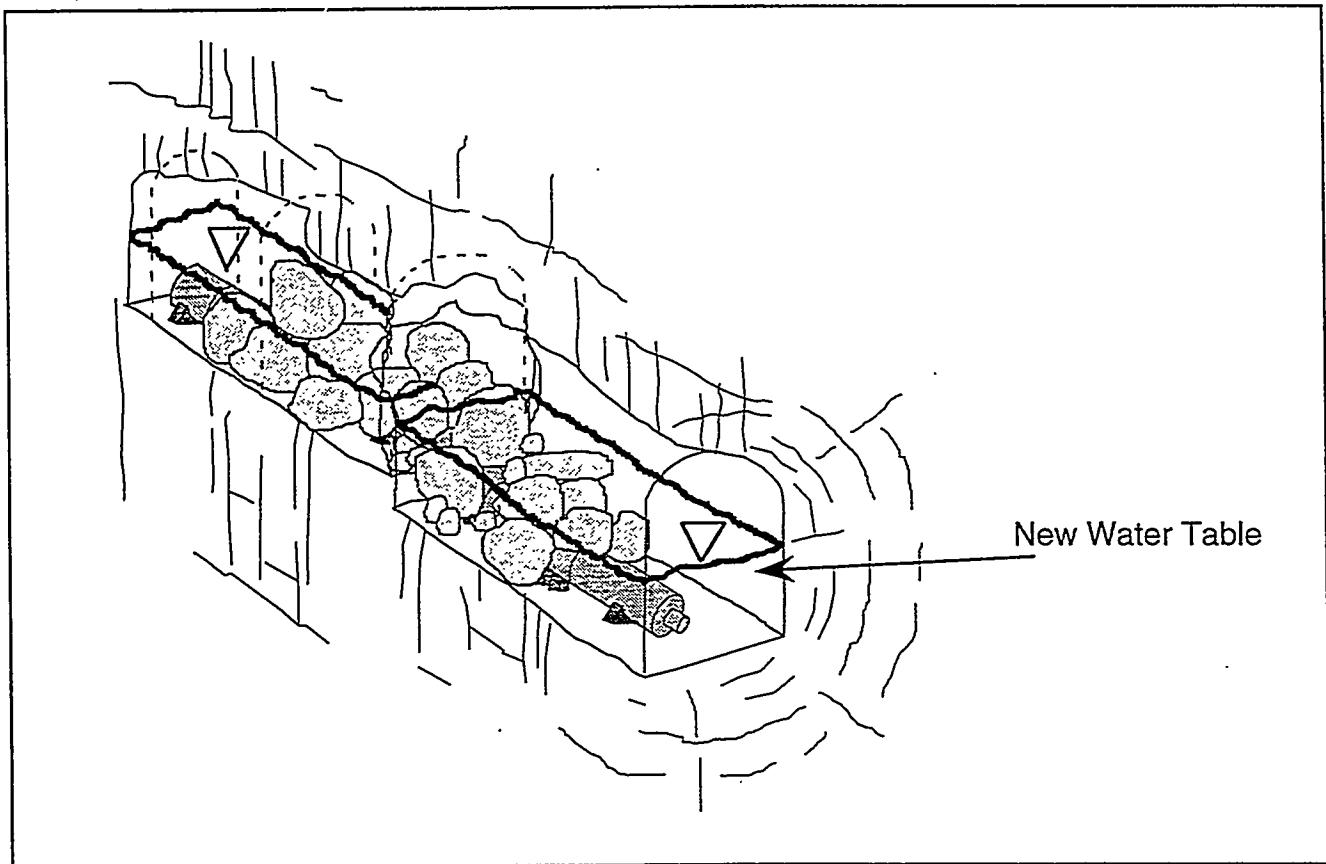


Figure 24. Flooded repository for the branch "Water Table Rises to Repository."

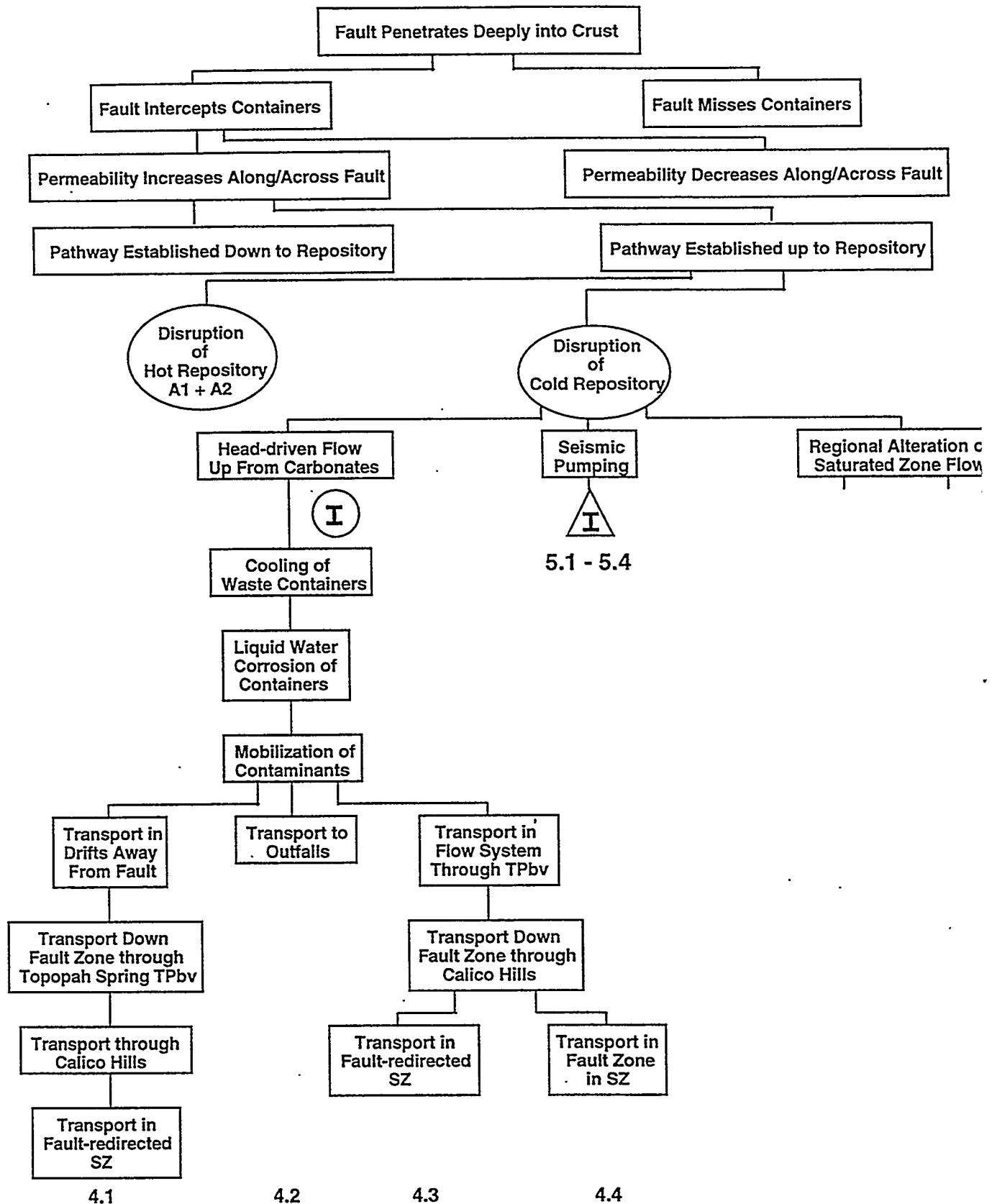
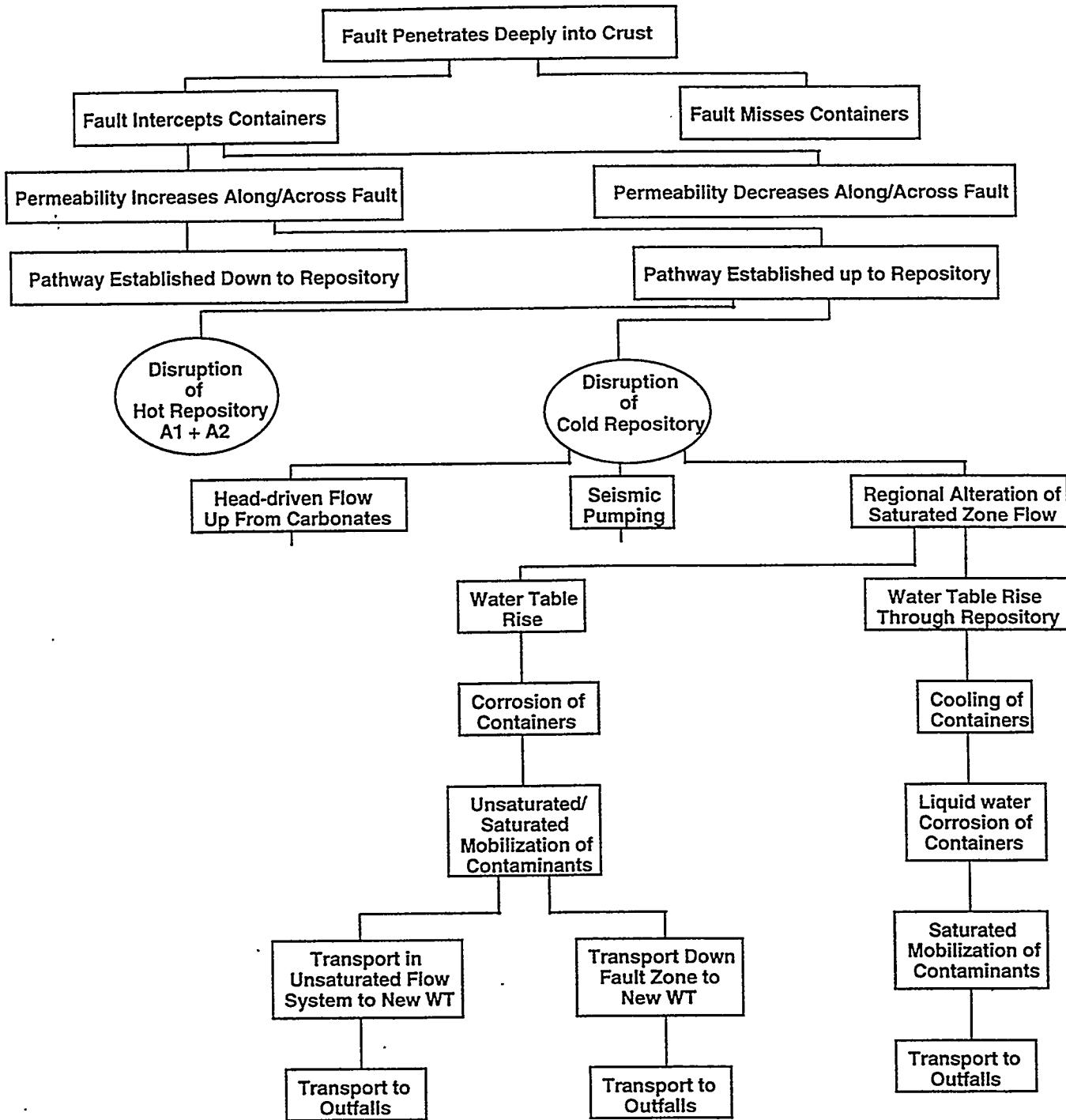


Figure 25. Tree Segment 4, Paths 4.1-4.4, and 5.1-5.4, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Intercepts Containers,"...



6.1

6.2

6.3

Figure 26. Tree Segment 6, Paths 6.1-6.3, "Tectonic Processes," "Fault Penetrates Deeply into Crust," "Fault Intercepts Containers," ...

branch, paths 4.1-4.4, continues with "Cooling of Waste Containers." There is then "Liquid Water Corrosion" and "Mobilization of Contaminants." The branch then divides into three branches to consider how the transport occurs in the drift: "Transport in Drift Away From Fault" (path 4.1), "Transport To Outfall" (path 4.2), and "Transport Down Fault Zone Through Topopah Spring basal vitrophyre" (paths 4.3, 4.4). Path 4.1 considers the case that the "Transport in Drift ..." leads to flow entering the flow system away from the fault zone, "Transport in Flow System Through Topopah Spring Basal Vitrophyre," followed by "Transport Through the Calico Hills" and "Transport in Fault Redirected Saturated Zone" as has been discussed earlier. Path 4.2 is concerned with immediate "Transport to Outfalls," namely springs and seeps, as a means of quickly reaching the accessible environment.

Paths 4.3 and 4.4 deal with transport down the fault zone, part of which is supplying water to the repository. They continue with "Transport Down Fault Zone Through Topopah Spring Basal Vitrophyre" and "Transport Down Fault Zone Through Calico Hills." Path 4.3 then proceeds with "Transport in Fault Redirected Saturated Zone" on the argument that the head distribution which provides the head-driven flow also alters the head distribution in the water table aquifer and redirects its flow. Path 4.4, considers the case that the primary transport is preferentially along the fault zone, "Transport in Fault Zone in Saturated Zone," to the accessible environment.

The next branch below "Disruption of Cold Repository" is "Seismic Pumping." The arguments for paths 5.1-5.4 are similar to those of paths 4.1-4.4, only the source of the water from depth is different. That difference will be reflected in the duration of the flow and its volume, since it is expected that "Seismic Pumping" would be a less durable process. The arguments are similar and will not be repeated.

Tree Segment 6

Paths 6.1, 6.2 and 6.3 (Figure 26) deal with "Regional Water Table Rise" with the possibilities of "Water Table Rise" and "Water Table Rise Through Repository." For paths 6.1 and 6.2, "Water Table Rise" elevates the water table above its current position, but below the repository. "Corrosion of Containers" is then dependent on the fluids brought to the repository by the disruption of the cold repository as is the "Mobilization of Contaminants," which is here described as "Unsaturated/Saturated Mobilization ...") to emphasize the connection to the water coming from above. Paths 6.1 and 6.2 separate to allow for "Transport in Unsaturated Flow System to New Water Table" and for "Transport Down Fault Zone to New Water Table." Both paths end with "Transport to Outfalls." Since there is some evidence that the water table has been higher in the past, perhaps 115m higher (Marshall and others, 1991; Paces and others, 1993; Quade and others, 1995), these are not necessarily new outfalls.⁴ The last path, 6.3, describes the

⁴ Marshall, B. D., J. S. Stuckless, Z. E. Peterman, and J. F. Whelan, 1993. "Isotopic Studies of Cavity Filling and Fracture Coating Minerals as an Aid to Understanding Paleohydrology," Yucca Mountain, NV, Nuclear Engineering Agency Proceedings for a Workshop on Paleohydrologic Methods and Their Application for Radioactive Waste Disposal, pp. 147-159.

case that the “Water Table Rises Through the Repository,” 200m or more above the current water table. Waste containers are not hot enough to generate two-phase flow but they may be substantially above the temperature of the water now reaching them. They will be cooled, “Cooling of Containers,” with some attendant circulation. We will then have “Liquid Water Corrosion of Containers” and “Saturated Mobilization of Contaminants.” Because of the lower temperatures “Mobilization ...” may result in a different speciation than the corresponding mobilization described in paths 3.3 and 3.4 for disruption of a hot repository.

This concludes the discussion of the branches of the event tree under “Permeability Increases Along/Across Fault.”

Permeability Decreases Along/Across Fault Tree Segment 7

We continue with the corresponding “Permeability Decreases Along/Across Fault” discussion. A permeability decrease means that the fault acts as a flow barrier both for the regional saturated flow systems(tuff aquifer and/or carbonate aquifer, together or independently) and for any lateral flow systems in the mountain. It also means that the fault is not an obvious preferential pathway either up or down from the repository. The development of the scenarios for “Disruption of a Hot Repository” is described in paths 7.1-7.6 in Tree Segment 7.

Tree Segment 7 (Figure 27) addresses two main branches, “Regional Alteration of Saturated Zone” and “Lateral Diversion Impeded.” For the first of these, the water table can rise because the regional flow fields are blocked or redirected by the impermeable fault (the current interpretation is that they are subparallel to the flow field; if this interpretation is true, this tree segment is eliminated). The now familiar distinction is made as to the level of the rise, through the repository or not (“Water Table Rises,” “Water Table Rises Through Repository”). Since the discussion of paths 7.1, and 7.2 are similar to paths 3.1, and 3.3, respectively, we refer the reader to those expositions. There is a noteworthy difference, however, for path 7.3. The large-scale convective cell may be laterally restricted by the impermeable fault which may affect its character (e.g., its mixing depth and its head distribution) and the outfalls to which contaminants are transported (Figure 28).

The second branch, “Lateral Diversion Impeded,” considers that lateral diversion of fluids down the dipping strata is impeded by the impermeable fault (Mualèm and Bear, 1978). Liquid accumulates against the fault zone; when the matrix is saturated, fracture flow begins. Essentially a perched-water system has been established. This flow is described by the elements “Locally Saturated and Fracture Flow at Fault” and “Locally Saturated and Fracture Flow to Repository.” Once the fluids are available to the disrupted repository, the paths continue as elements C, D, E (paths 7.4, 7.5, 7.6), as discussed in Tree Segment 2.

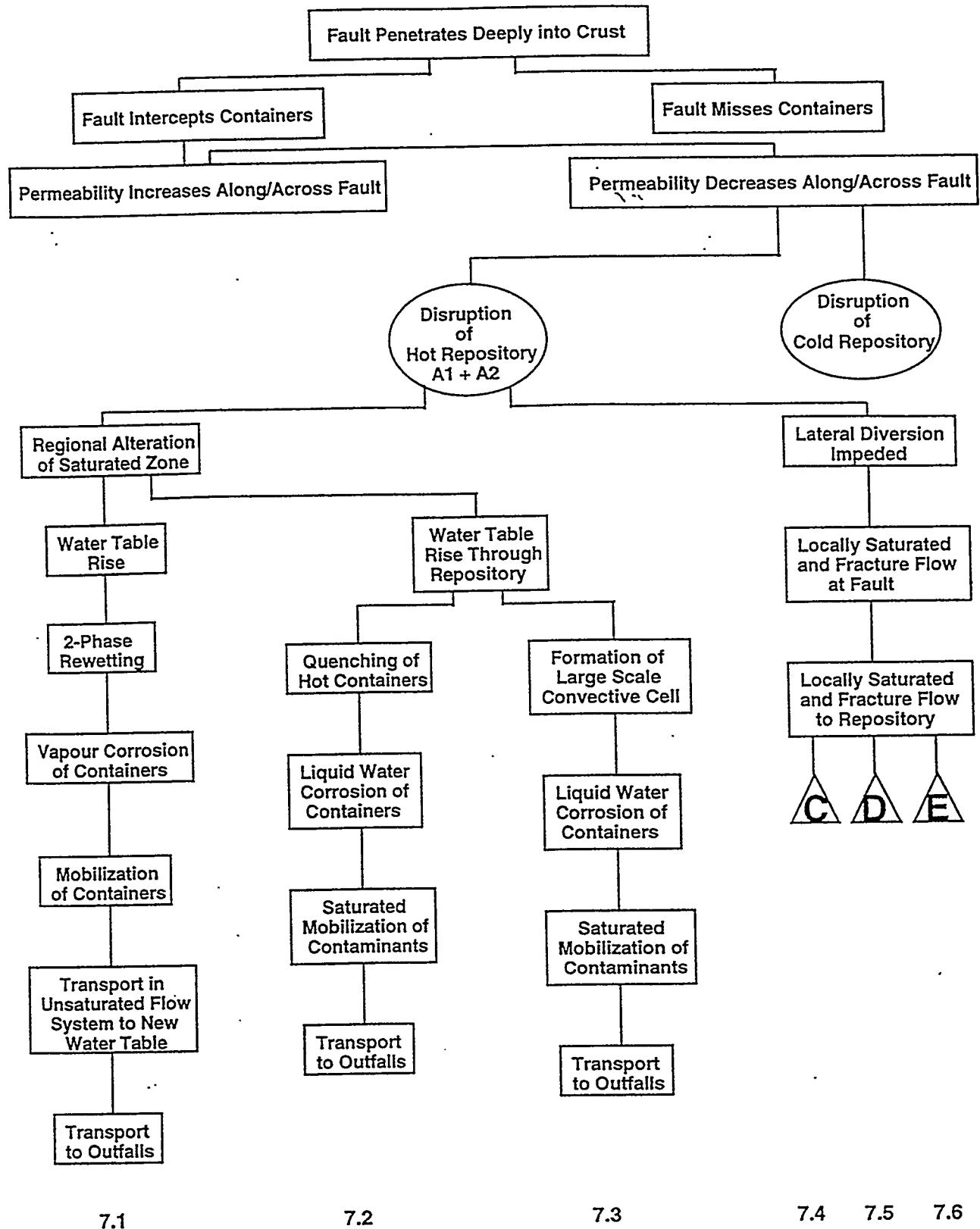


Figure 27. Tree Segment 7, Paths 7.1-7.6, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into the Crust," "Fault Intercepts Containers,"...

Tree Segment 8

Tree Segment 8 (Figure 29) continues the discussion for the case of "Disruption of a Cold Repository." Again there are two branches, "Regional Alteration of the Saturated Zone" and "Lateral Diversion Impeded" with two paths under each. For "Regional Alteration ...," the two flow systems, the tuff aquifer (Tertiary aquifer) and the carbonate aquifers, apparently are distinct; however, there are few data in the vicinity of Yucca Mountain in the carbonate aquifers. The dam represented by the fault could thus force a water level rise on either side. Path 8.1 describes the "Water Table Rise" which does not reach the waste. Mobilization then depends on the flow system (locally saturated or unsaturated) which reaches the drifts from above. Similarly, transport to the water table, described in the element as unsaturated, may also be in a locally saturated system. Once at the new water table, the contaminants are transported to outfalls. One might expect that paleo-spring and seep sites would be dominant release sites; however, data on such sites are few and there appear to be no volumetric estimates available. Path 8.2 considers the "Water Table Rise Through the Repository." It continues allowing for cooling of containers to the temperature of the rising water. The mobilization of contaminants is in a saturated system and the transport proceeds to outfalls. Whether there are outfalls different from those of Path 8.1 is unknown.

Paths 8.3, 8.4 and 8.5 are concerned with the consequences of impeding any lateral flow down dip. Blockage of such flow by the fault can generate locally saturated flow or fracture flow outside the fault, as discussed in Tree Segment 7. Path 8.3 continues with "Drip on Containers" and "Container Corrosion to Failure." Transport of contaminants then occurs in the flow system exiting the drifts and the contaminants are then carried to outfalls. Path 8.4 continues with "Local Flooding" - the volume of water and damage to the drift allowing one or more containers to sit in a water bath - and ends with transport to outfalls. Path 8.5 assumes that the "Locally Saturated and Fracture Flow at Fault" feeds an unsaturated flow system which reaches the containers through the rock fall. While the flow to the containers is expected to be unsaturated there is possibility for generation of drip onto containers (Philip and others, 1989), depending on the geometry of the collapse (or stoping) at the fault zone and various rock properties. This path continues with unsaturated mobilization and transport to the water table. As with the other paths of this Tree Segment 8, contaminants reach the accessible environment through outfalls.

This concludes the discussion of "Fault Intercepts Containers."

Fault Misses Containers Tree Segments 9-16

Most of the waste containers in the repository will not be in the fault zone of a new fault; they make up the population of this category. We expect that the fault will produce generally distributed rock fall away from the fault zone. This rock fall will be less extensive and be less likely to penetrate the altered region around the drifts. The effect on the hydrothermal flow systems, condensate zone and heat pipes will be less pronounced. The most profound change will be that any flow or transport which is carried up or down the fault zone must now be carried down the drift, invert, and the mechanically disturbed

zone around the drift to and from the fault zone. Contaminants can enter the flow system extant around the drifts, or they can move down the drift to the fault zone. In effect the residence time in the flow field for contaminants has been increased. Otherwise, the descriptions of the most of the scenarios, (the paths), are the same. The Tree Segments are included with that change: we refer the reader to the earlier descriptions.

Tree Segment 9 (Figure 30) develops the case that “Permeability Increases Along/Across the Fault” and a “Pathway is Established Down to the Repository.” This development allows connection of sources above the repository to the drifts. “Disruption of the Hot Repository” includes less extensive rock fall onto waste containers, since there are no containers located in the fault zone. Stoping up the fault can still occur and the hydrothermal flow driven by container heat altered in response.

Path 9.1 continues with “Drip on Waste Containers,” “Container Corrosion ...” and “Mobilization ...,” but because of the limited amount of water -drip- and the fact that the fault zone is away from the container, transport is in the flow system existing or developing around the altered drift, (“Transport in Flow System”). Similarly, transport through the Topopah Spring basal vitrophyre and the Calico Hills units are in the existing unsaturated or locally saturated flow systems. Transport in the saturated zone is in a flow system altered by movement on the old fault.

Paths 9.2, 9.3 and 9.4 require “Local Flooding of the Drift” to supply sufficient water. There is the usual “Saturated Corrosion ...” and “Saturated Mobilization” The paths then divide to consider the cases that transport occurs by entry into the flow system away from the fault (path 9.2) or by “Transport Down Drifts to the Fault Zone” to flow down the fault zone to the water table. Transport in the saturated zone can then be either in a flow system redirected by the movement on the old fault (path 9.3) or confined to the fault zone itself (path 9.4).

Path 9.5 considers the possibility that “Pathway Established Down to Repository” and the “Disruption of the Hot Repository” produce “Enhanced Water Vapor Flow to the Drifts,” that is, the path change allows enough water to arrive through the vaporization zone to produce water vapor to corrode the containers but requires a larger volume or more time to elapse to allow liquid water to reach the remains of the container to be mobilized. Once liquid water is available, the remainder of the branch follows G, the bottom of branch 9.1.

The remaining paths, (9.6-9.10), require “Disruption of the Cold Repository,” namely enhanced or accelerated rock fall on containers away from the fault. The containers may be damaged, or ruptured and are now in contact with rock. Path 9.6, “Drip on Waste Containers” and paths 9.7, 9.8, and 9.9, “Local Flooding of Drift” continue with elements like those in paths 9.1-9.4. Path 9.10 examines the problem of “Unsaturated Flow Through the Rock Fall to the Waste Containers.” This includes the waste containers in a much slower flow system than the previous paths, 9.1-9.9, since flow is limited to the rock matrix. The path continues with corrosion, mobilization and transport in this unsaturated flow system until arriving at the water table. The reduced temperature of the source, the waste containers, is expected to affect reaction rates and speciation of

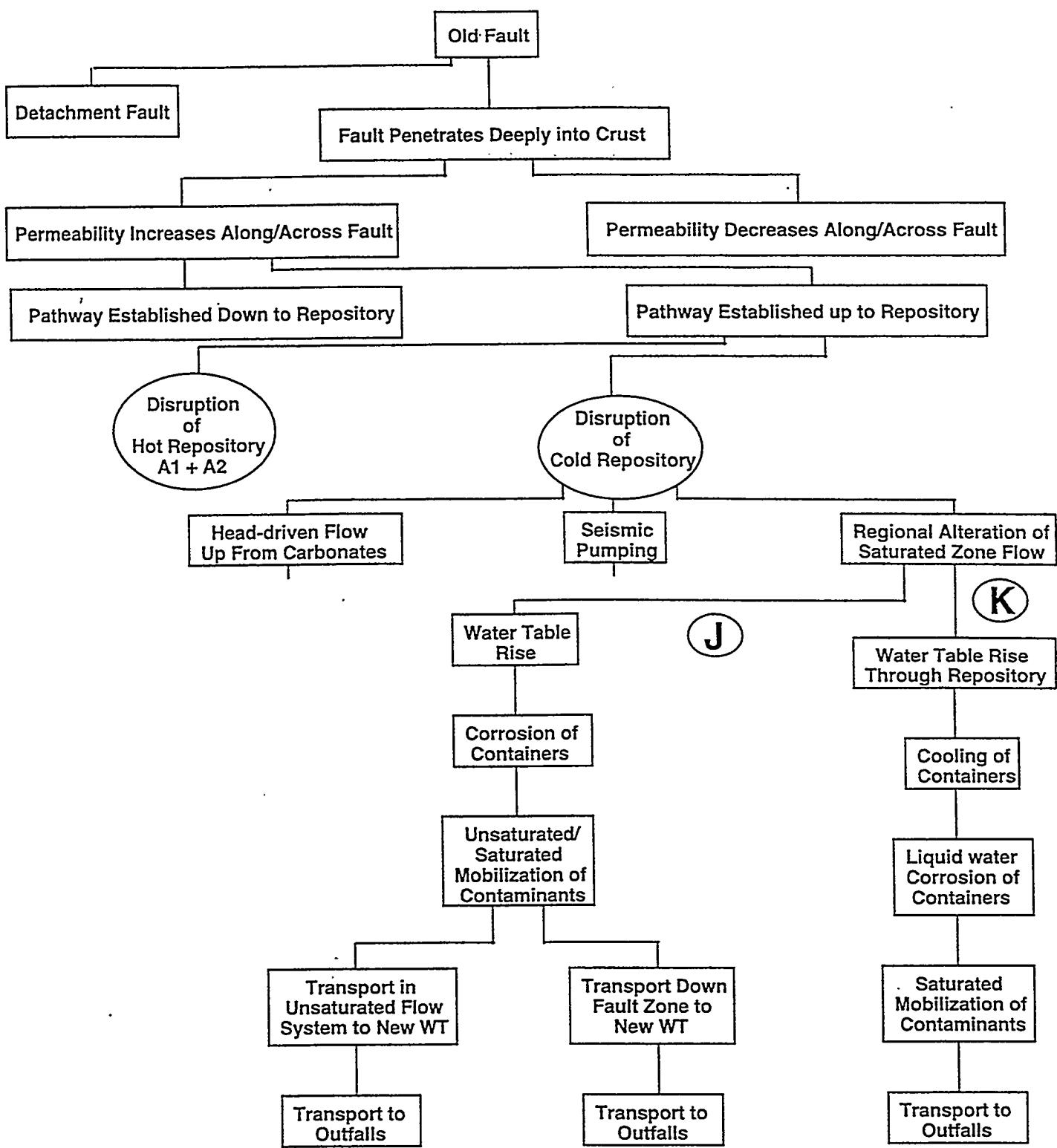
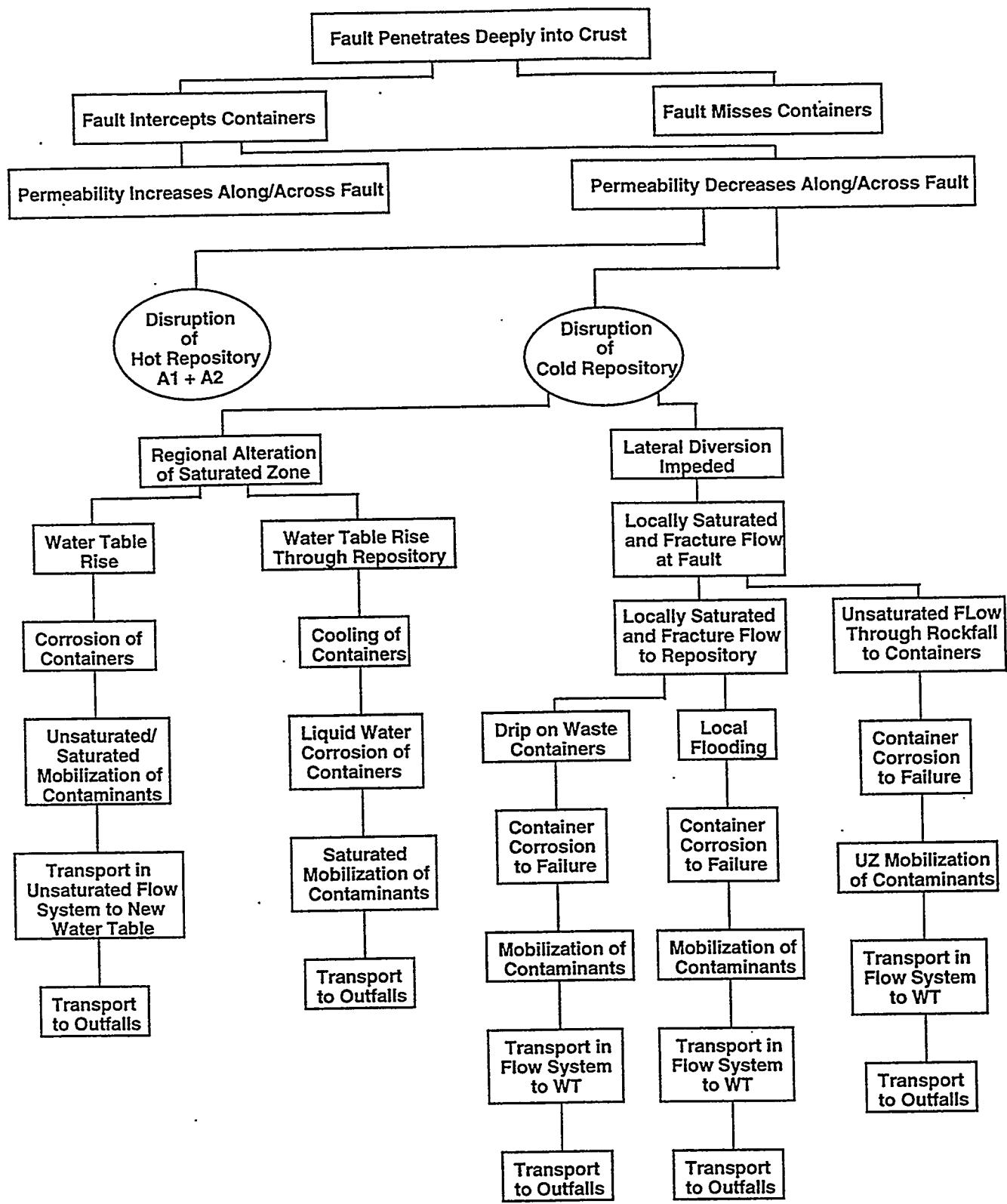


Figure 28. Sketch of the relative locations of faults likely to control the lateral extent of a convective flow system.



8.1

8.2

8.3

8.4

8.5

Figure 29. Tree Segment 8, Paths 8.1-8.5, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into the Crust," "Fault Intercepts Containers,"...

contaminants and the distribution of contaminants between solutes and colloids, so that mobilization and transport may differ from those for the disrupted hot repository.

The branches parallel to “Pathway Established Down to Repository” are below “Pathway Established Up to Repository.” These are intended to examine the circumstances that allow water to flow up from below the repository. Tree Segments 10-15 (Figures 31-35) show these paths, which mimic those discussed in Tree Segments 2-6. The changes are, the fault zone does not intersect waste containers, the rock fall is not as severe as at the fault zone, and flow reaching containers must move down the drift away from the fault zone in order to reach the waste containers. With those changes in mind the reader is referred to the earlier discussion of Tree Segments 2-6.

In addition to “Permeability Increases Along/Across Fault,” the tree has the alternative that the “Permeability Decreases Along/Across Fault.” In this case no preferential paths are established up to or down to the repository. However, there are two ways identified in Tree Segments 15 and 16 (Figures 35, 36) that the flow system to or away from the repository can be altered to increase releases.

Both Tree Segments 15 and 16 identify “Regional Alteration of Saturated Zone” and “Lateral Diversion Impeded” as possible mechanisms for increasing releases. The paths in these tree segments are similar to those in Tree Segments 7 and 8 discussed earlier. They differ by the changes that are required implicitly in each element of the branch because the containers affected are outside the fault zone. The paths are shown but are not discussed.

5.2 Old Faults

Discussion of the section of the event tree shown in Figure 37, “Tectonic Processes,” “Old Fault Through Repository Block.”

Old faults are considered separately because it is not expected that waste containers will be emplaced in fault zones identified in the underground workings and thus no containers will be intersected by movement on old faults. Consequently, the branches in the “New Fault Through Repository Block” branch that involve “Fault Intersects Container” are absent from the “Old Fault Through Block.”

Tree Segment 17 begins from “Old Fault” and divides to identify two different kinds of old faults, “Detachment Faults” and “Faults Which Penetrate Deeply into the Crust.” Detachment faults are considered because of previously proposed tectonic models (e.g., Scott, 1990). However, studies recently completed by the USGS (Simonds and others,

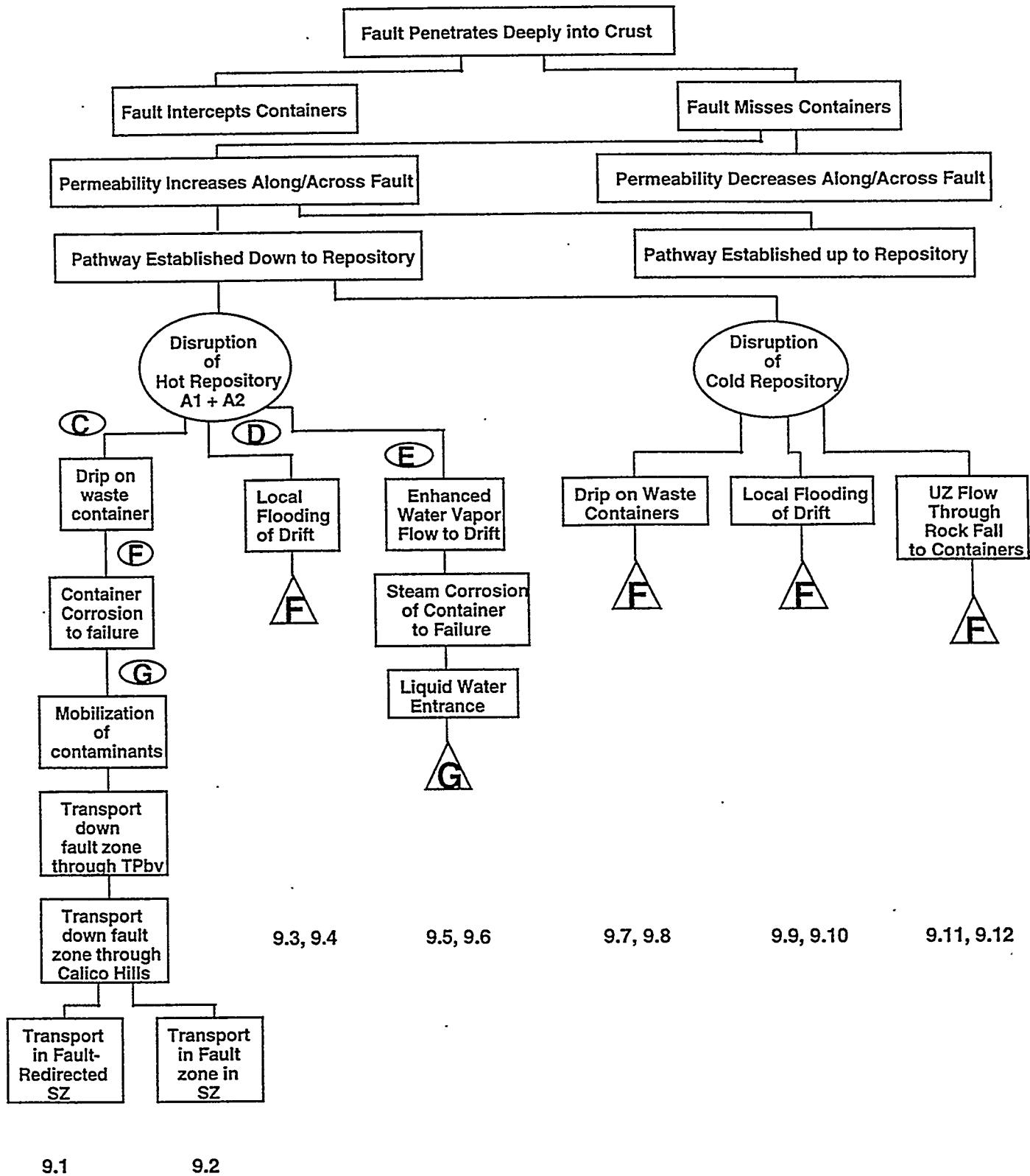


Figure 30. Tree Segment 9, Paths 9.1-9.12, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into the Crust," "Fault Misses Containers,"...

1995, and Brocher and Hunter, 1996) have failed to yield evidence consistent with that model. For the majority of fault slip determinations in the western Great Basin, the earthquakes are very small and do not represent the majority part of earthquake strain. That is represented by the few large earthquakes. In the Yucca Mountain/Crater Flat domain, it is clear from fault studies that the majority of discrete fault slip in this domain is dip/slip. There is also significant but lesser strike/slip deformation in this domain, which is expressed as an oblique component of slip on those dip/slip faults. Future earthquakes are most likely to have predominately dip/slip focal mechanisms, but strike/slip faults may occur. Since the regional stress state is known to change slowly (Zoback and others, 1981; Bellier and Zoback, 1995), we anticipate that this style will continue. If old listric faults do exist at Yucca Mountain, fault movement on them would be expected to produce much different alteration to the saturated-zone flow system than faults which penetrate deeply into the crust. It is this difference which leads us to consider detachment faults separately.

5.2.1 Detachment Faults (“Old Faults,” “Detachment Faults”)

Starting with “Detachment Fault,” Tree Segment 17 (Figure 38) divides to recognize two possible near-surface locations for the sub-horizontal part of the fault. These locations are “Above the Carbonates” and “Below/Through the Carbonates.” Paths 17.1-17.12 consider the case of “Above the Carbonates” first. The tree segment continues with “Permeability Increases Along/Across Fault.” A decrease of permeability would further isolate the carbonate aquifer from the overlaying tuffs; they are already isolated, at least at UE-25p#1 where the head is 20 m higher in the carbonates than in the tuffs (Craig and Robison, 1984). While this isolation may not be universally true, discussion of the changes would require consideration of alternative conceptual models of the large hydraulic gradient as done by Fridrich and others (Fridrich and others, 1994a) and possible upwelling in places along Solitario Canyon Fault and Bow Ridge Fault to the west and east of the repository block, respectively. The alteration of permeability across those faults would affect the location of the water table at the repository, but data are so sparse and there is no supporting modeling, so we will omit further discussion of this possibility.

Since the head difference between the carbonates and tuffs is on the order of 20 m, the principal flow reaching the repository is from above, described as “Flow Down to Repository.” The flow, which arrives at a disrupted repository, can be unsaturated or locally saturated flow. Since there are no containers located in the fault zone, the rock fall associated with the disruption of the repository is generally distributed throughout the drifts. The discussion of “Disruption of Hot Repository” proceeds similarly to that of the discussion for paths 1.1-1.6, recognizing that rock fall exposing the condensate zone or removing the altered rock around the drifts is less likely. The effective size of the drifts is increased, contact of rock with containers is common and the likelihood of container damage due to rock fall is pervasive.

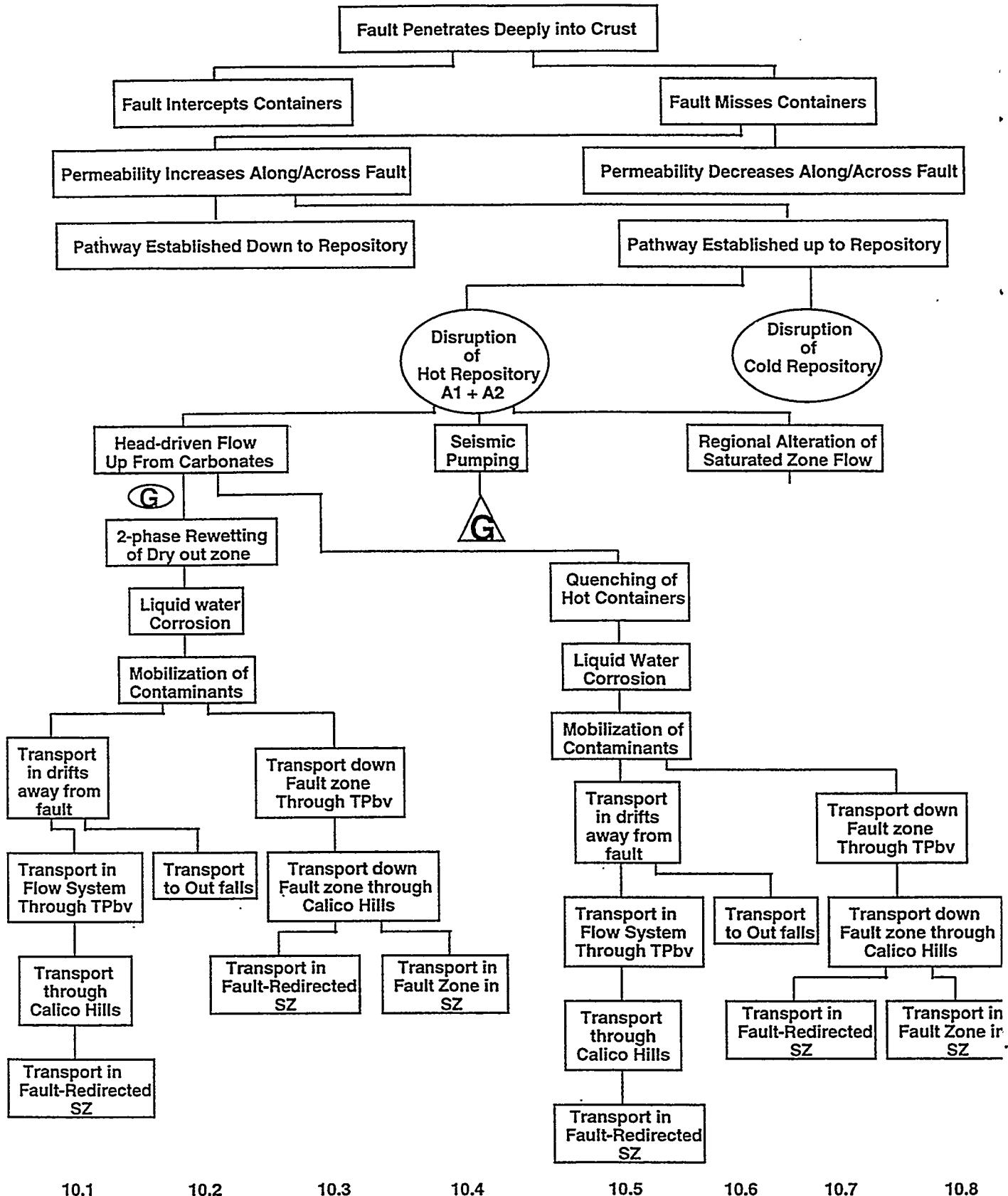


Figure 31. Tree Segment 10, Paths 10.1-10.8, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Misses Containers,"...

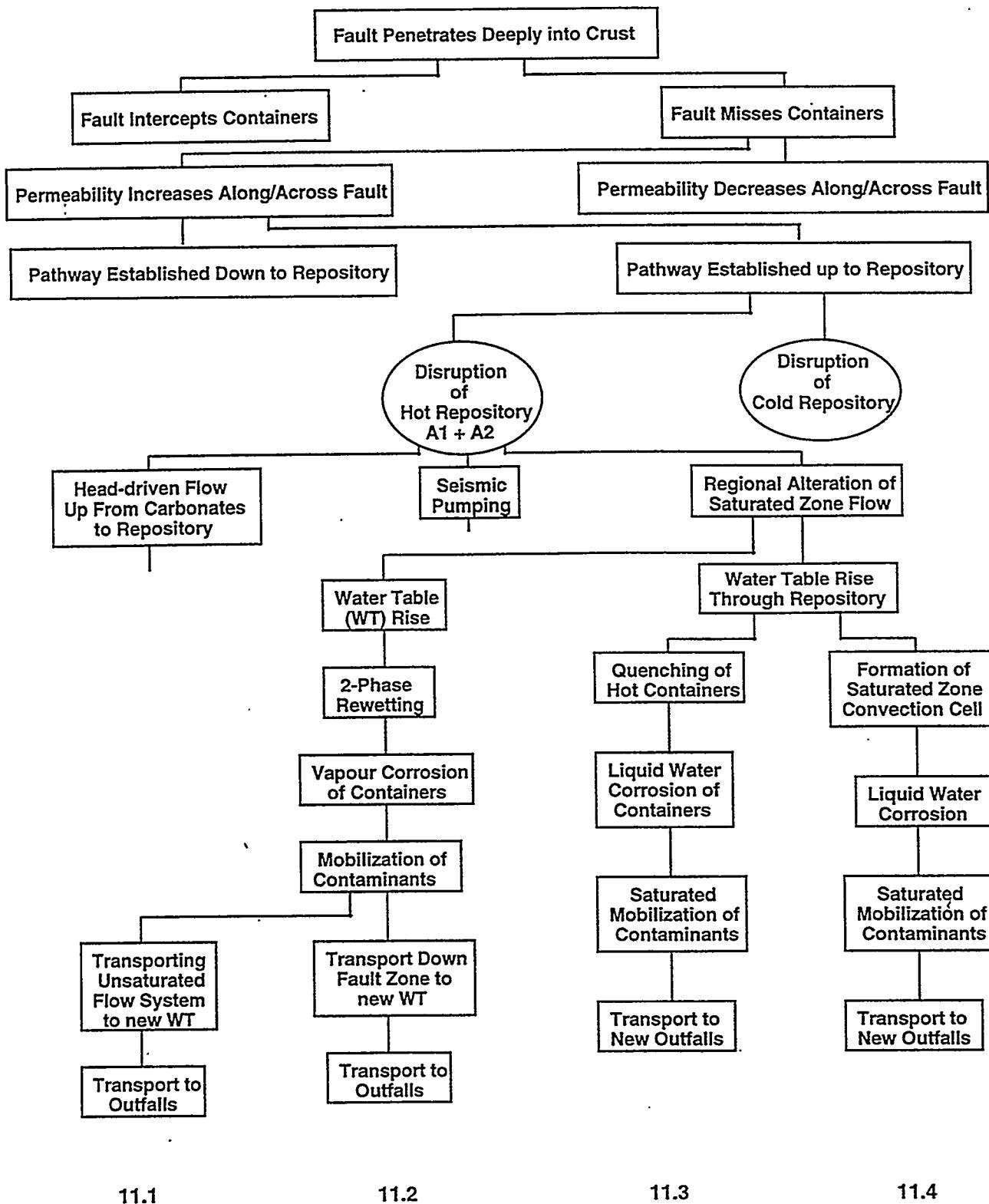


Figure 32. Tree Segment 11, Paths 11.1-11.4, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Misses Containers,"...

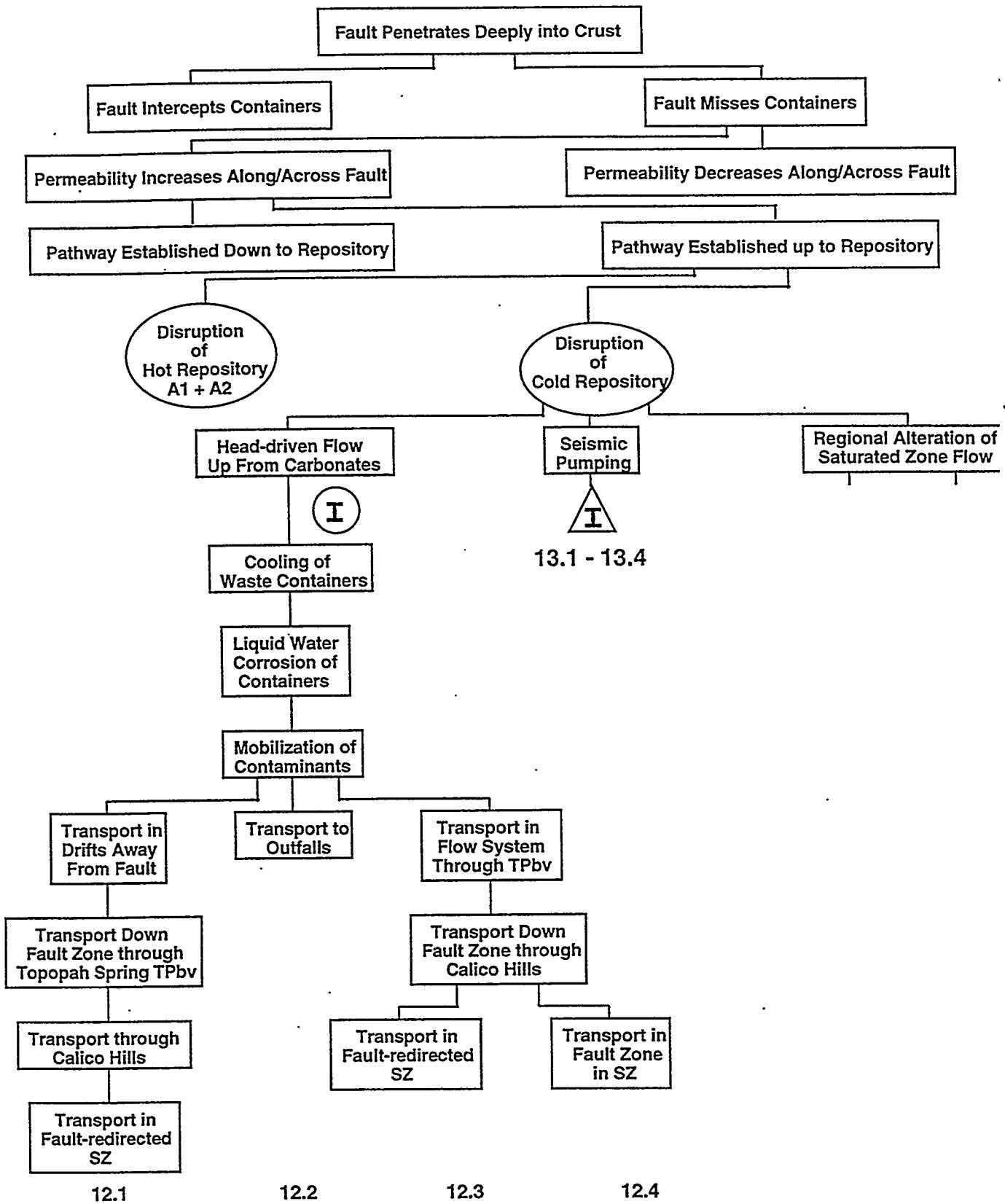


Figure 33. Tree Segment 12, Paths 12.1-12.4, and 13.1-13.4, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Misses Containers," ...

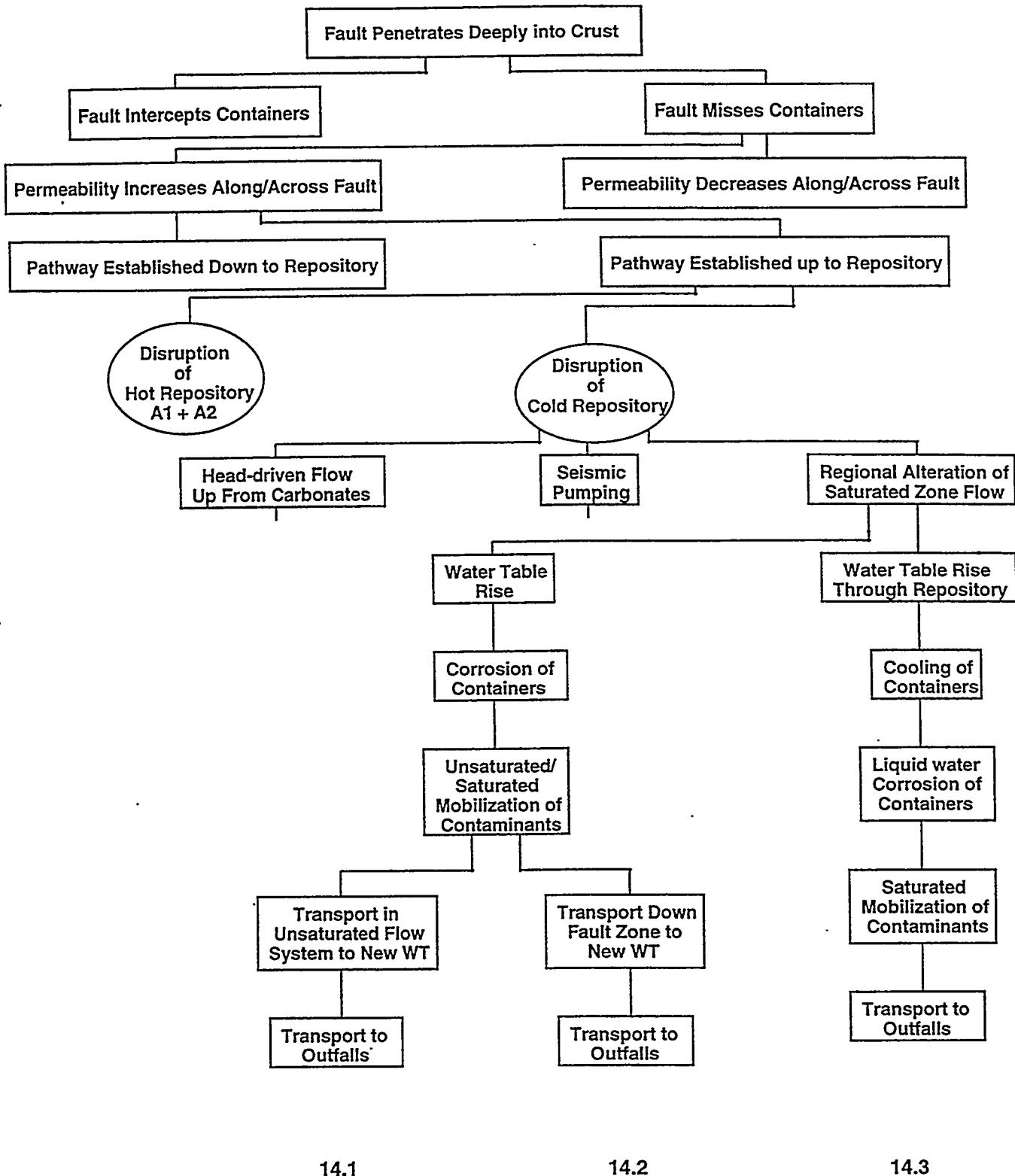


Figure 34. Tree Segment 14, Paths 14.1-14.3, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Misses Containers," ...

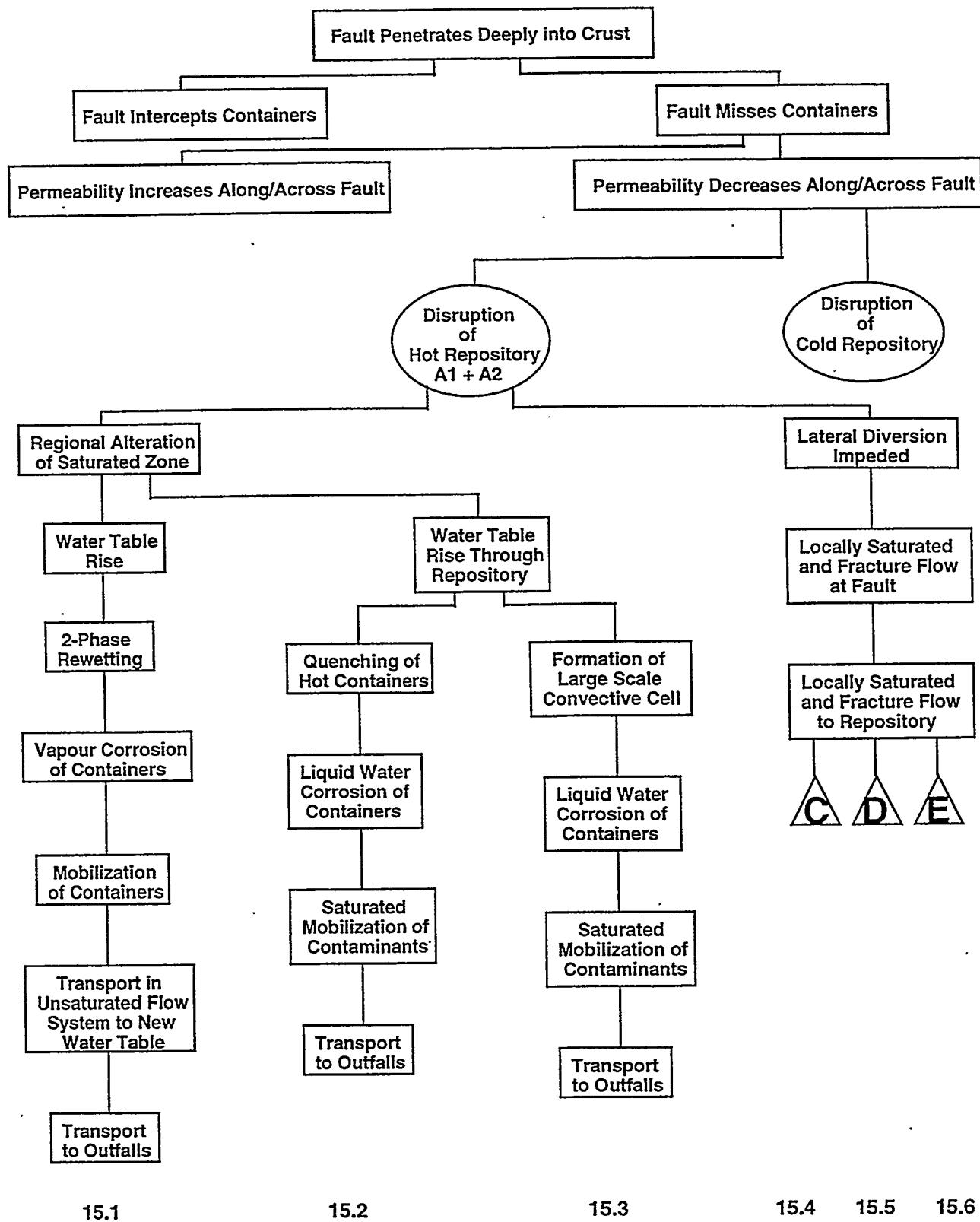


Figure 35. Tree Segment 15, Paths 15.1-15.6, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Misses Containers," ...

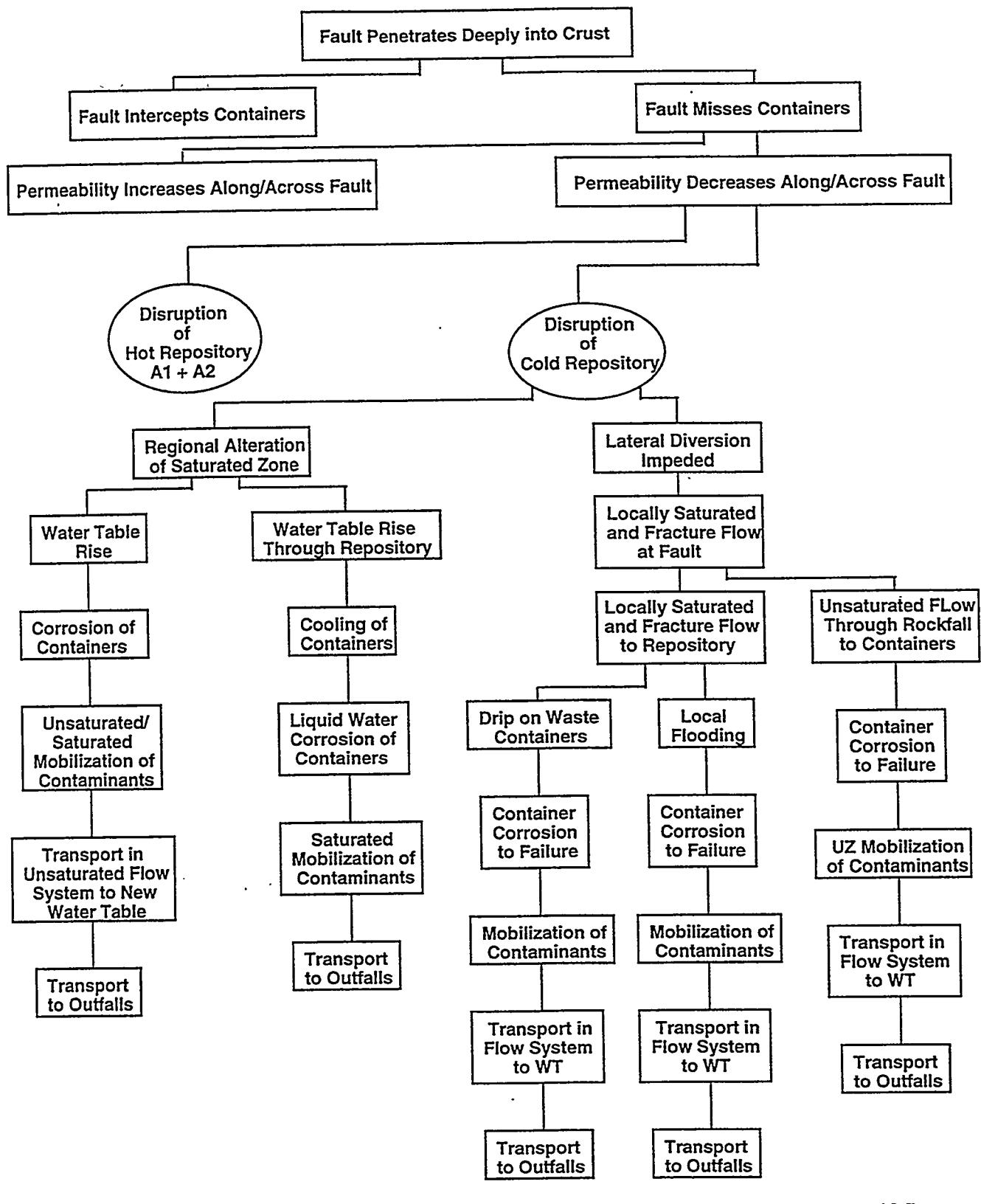


Figure 36. Tree Segment 16, Paths 16.1-16.5, "Tectonic Processes," "New Fault," "Fault Penetrates Deeply into Crust," "Fault Misses Containers," ...

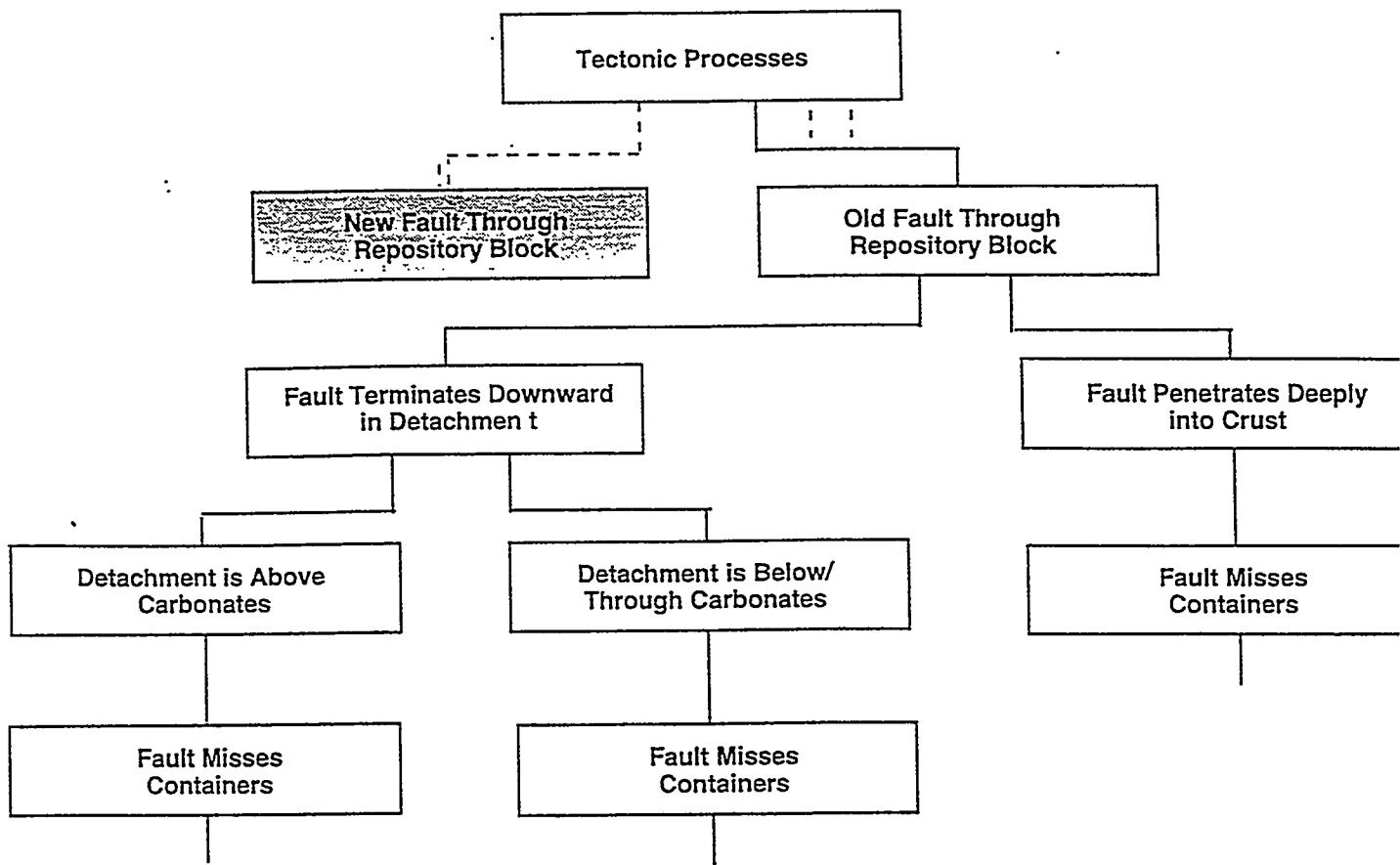


Figure 37. Upper Tree Segment

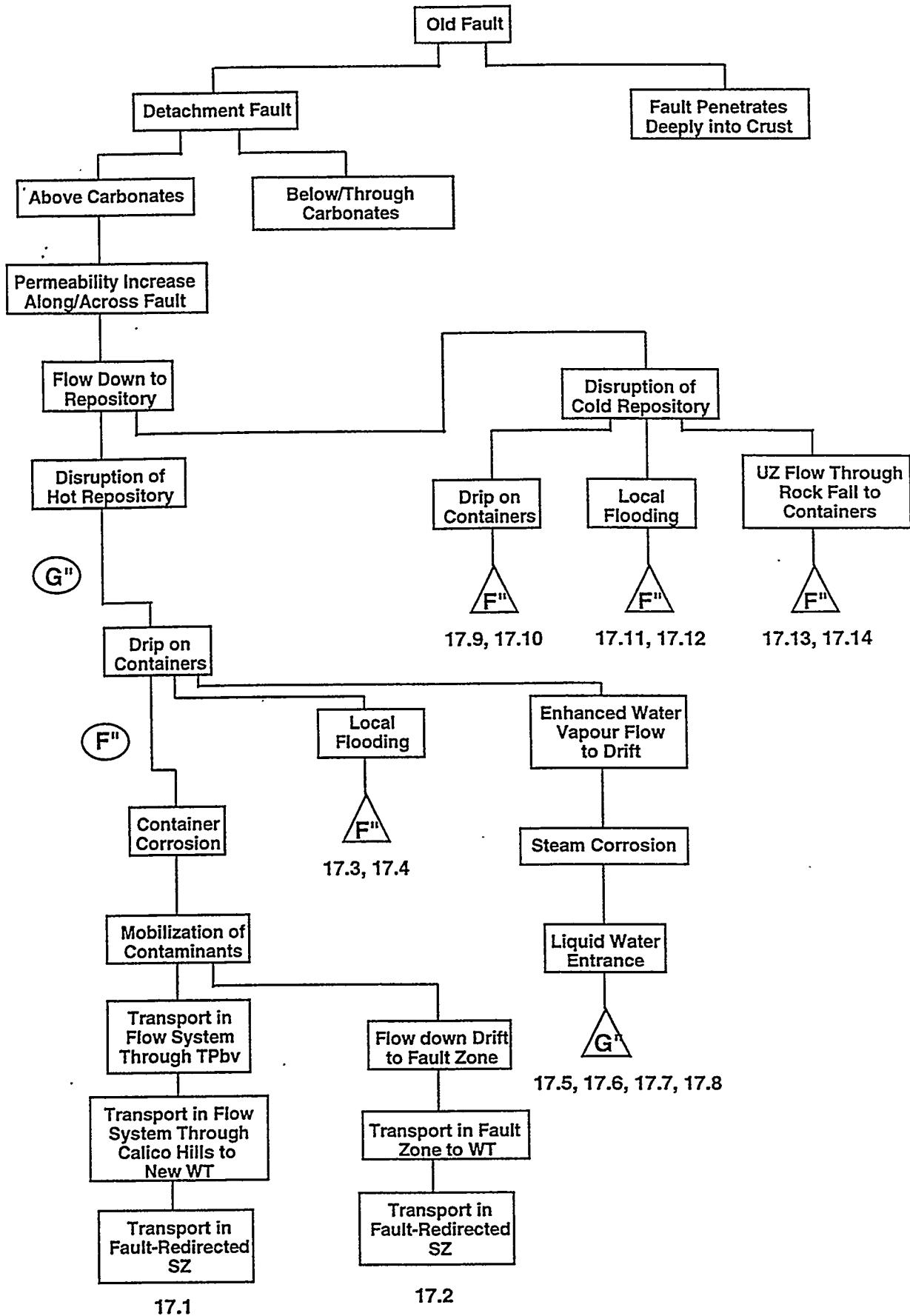


Figure 38. Tree Segment 17, Paths 17.1-17.14, "Tectonic Processes," "Old Fault," "Detachment Fault,"...

The tree segment continues with “Drip onto Containers,” “Local Flooding” and “Enhanced Water Vapor Flow to Drift” as branches, similar to the structure of tree segment 1 (paths 1.1-1.6). “Container Corrosion” and “Mobilization of Contaminants” are as before. Since the flow from the carbonates has presumably established a new water table, we have “Transport in Flow System Through TPbv” and “Transport in Flow System Through Calico Hills to New Water Table.” The path ends with “Transport in Fault-Redirected Saturated Zone.” We presume that the connection between carbonates and tuffs and the change of head at the water table will redirect the flow. If the head in the carbonates is below that of the tuffs along the flow direction then it also would be possible for contaminants to enter the sub-horizontal fault and be transported as if in a well constrained flow channel.

Detachment Fault Below or Through the Carbonates (“Old Fault,” Detachment Fault,” “Fault Below/Through Carbonates”)

Based on the occurrence of carbonate exposures at Bare Mountain to the west and the extension that this region has undergone, it is possible for the sub-horizontal section of a listric fault to underlie Yucca Mountain. Strike/slip or dip/slip movement on such a fault under or through the carbonates would then be expected to reorganize the flow system at depth producing a series of scenarios like the paths of Tree Segment 18. There are no drill hole data supporting interpretations for the existence of such a fault below Yucca Mountain, that we are aware of. We will defer consideration of such scenarios until such information becomes available to provide guidance on what might be important to consider.

5.2.2 Other Faults

Fault Penetrates Deeply into the Crust (“Old Faults,” “Fault Penetrates Deeply into the Crust”)

This set of paths in Tree Segments 18, 19, 20, 21, 22 and 23 addresses movement on an old fault through the repository block which penetrates deeply into the crust (Figures 39-44). The movement is likely to be strike/slip or dip/slip as has been identified as the current style in this region. Since no waste containers are likely to be placed in an identified fault zone, all of these scenarios are similar to those discussed for “New Fault,” “Fault Penetrates Deeply into the Crust,” “Fault Misses Containers.” The reader is reminded, however, that the probability of occurrence and specific properties like vertical offset of units may be quite different for new faults than for old faults.

5.3 Changing Stress State at Repository Block

The branches described here and expanded in figures 45 and 46 are intended to recognize that the stress state of the repository block could result in strains which alter the hydrologic flow field above and below the repository and alter its connection to regional flow fields.

Discussion of the section of the tree shown in Figure 45, Tree Segment 24, "Tectonic Processes," "Changing Stress State at Repository Block," "Repository-Heat Generated Thermal Stress."

This branch, expanded in Figure 45, recognizes that "Repository-Heat Generated Stress" needs to be accounted for. Calculations (Jung and others, 1994) indicate that the top of an elastic mountain would rise some 30 cm in about 300 years. A net total rise of about a meter would be expected.

Strain to accommodate the stress may be ". .Accommodated Along Bounding Faults" or

"Accommodated in the Repository Block" by adjustment along existing fractures. In the first case the idea is that the mechanical adjustment to the thermal stress, thermal expansion, occurs along the faults bounding the repository because the blocks composing the mountain are more or less locked. An adjustment of the order of a meter along the bounding faults, e.g., Solitario Canyon Fault or Bow Ridge Fault or Ghost Dance Fault, is a substantial movement for the period of concern of a few thousand to 10,000 years. Relaxation after the thermal period of the repository is over is not likely to be completely reversible, so residual alteration is expected. The effect of such thermally induced fault movement is presumed to be "Alteration of Regional Flow System." The locus of the movement is along the faults adjacent to the repository. Vertical movement of a meter is expected to alter permeability across and up the faults. Such alteration could allow connection to the carbonate aquifers and could redirect flow in the tuff aquifer. Two branches are considered to describe this alteration, "Alteration of the Large Hydraulic Gradient" and a more general "Alteration of Transmissivity of Faults Not in the Block." The large hydraulic gradient is specifically called out because its controls are uncertain; they may even not be fault related (Fridrich and others, 1994a). Paths 24.1-24.3 for "Disruption of Hot Repository" and paths 24.4-24.6, for "Disruption of a Cold Repository" continue in the usual way to "Rise of Water Table," "Rise of Water Table to Repository," and "Redirection of the Saturated Zone Flow System."

Similarly, paths 24.7-24.12, below "Alteration of Transmissivity of Faults Not in Block" continue in the same way.

The second choice for how the stress is accommodated by strain is "Strain is Accommodated in Repository Block." In this case two options are included for effects of that strain, "Deviatoric Stress Alters with Time," and "Cyclic Release and Redevelopment of Stress" (for discussion of Deviatoric Stress see for example: Hobbs and others, 1976; Means, 1976; Turcotte and Schubert, 1982). For "Deviatoric Stress..." the time-dependent development of the stress is explicitly recognized. Loading of the repository is expected to proceed from north to south across the block. The thermal loading will follow the physical loading, generating a "stress envelope" moving slowly outward from the drifts. This movement generates a moving strain envelope, described as "Moving Location of Strain Alteration of K (hydraulic conductivity) and S(storativity). The effect is to alter the flow system by changing hydraulic parameters, for example, opening fracture connections to perched water zones, or opening fractures at the surface

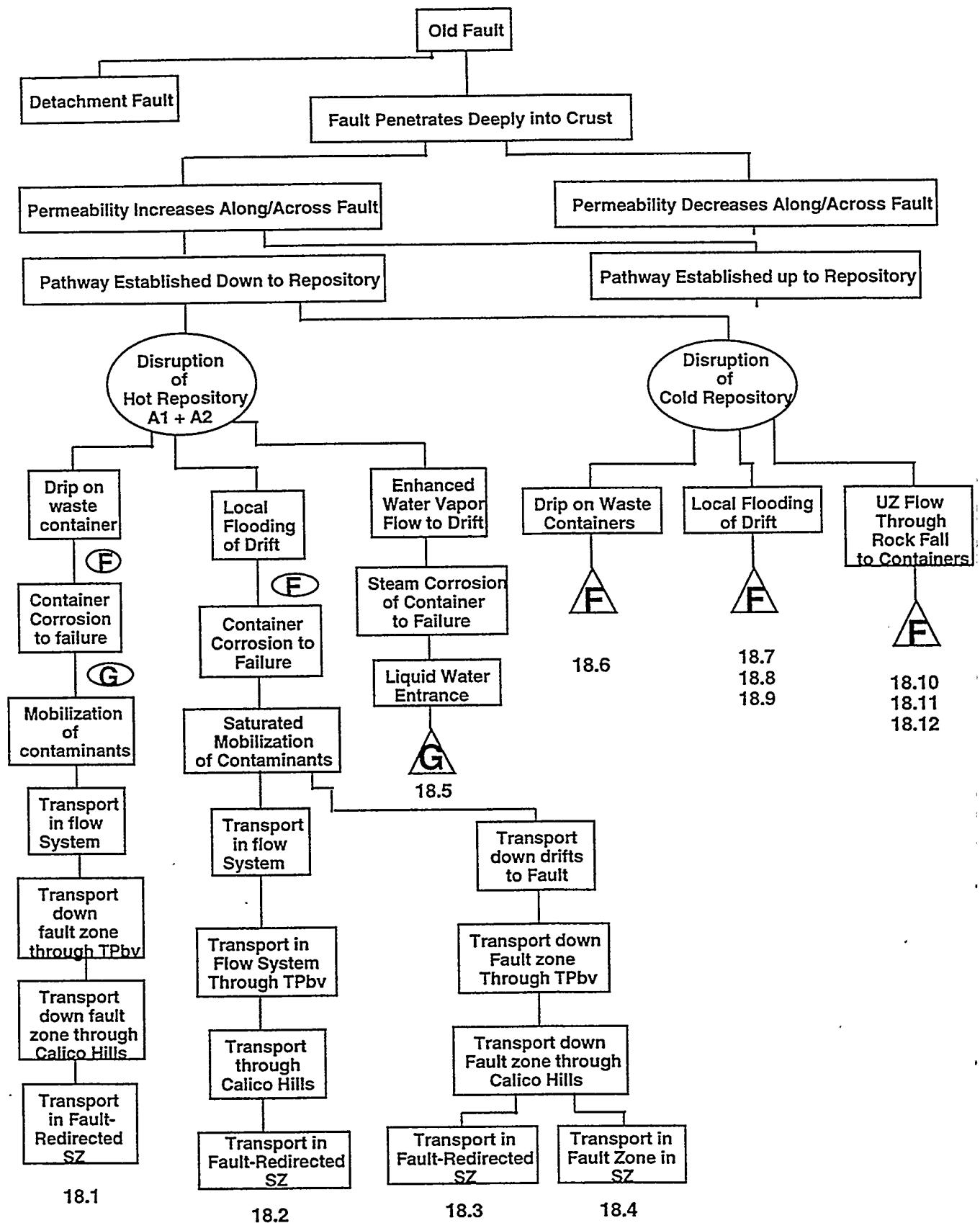


Figure 39. Tree Segment 18, Paths 18.1-18.12, "Tectonic Processes," "Old Fault," "Fault Penetrates Deeply into Crust," "Permeability Increases Along/Across Fault," ...

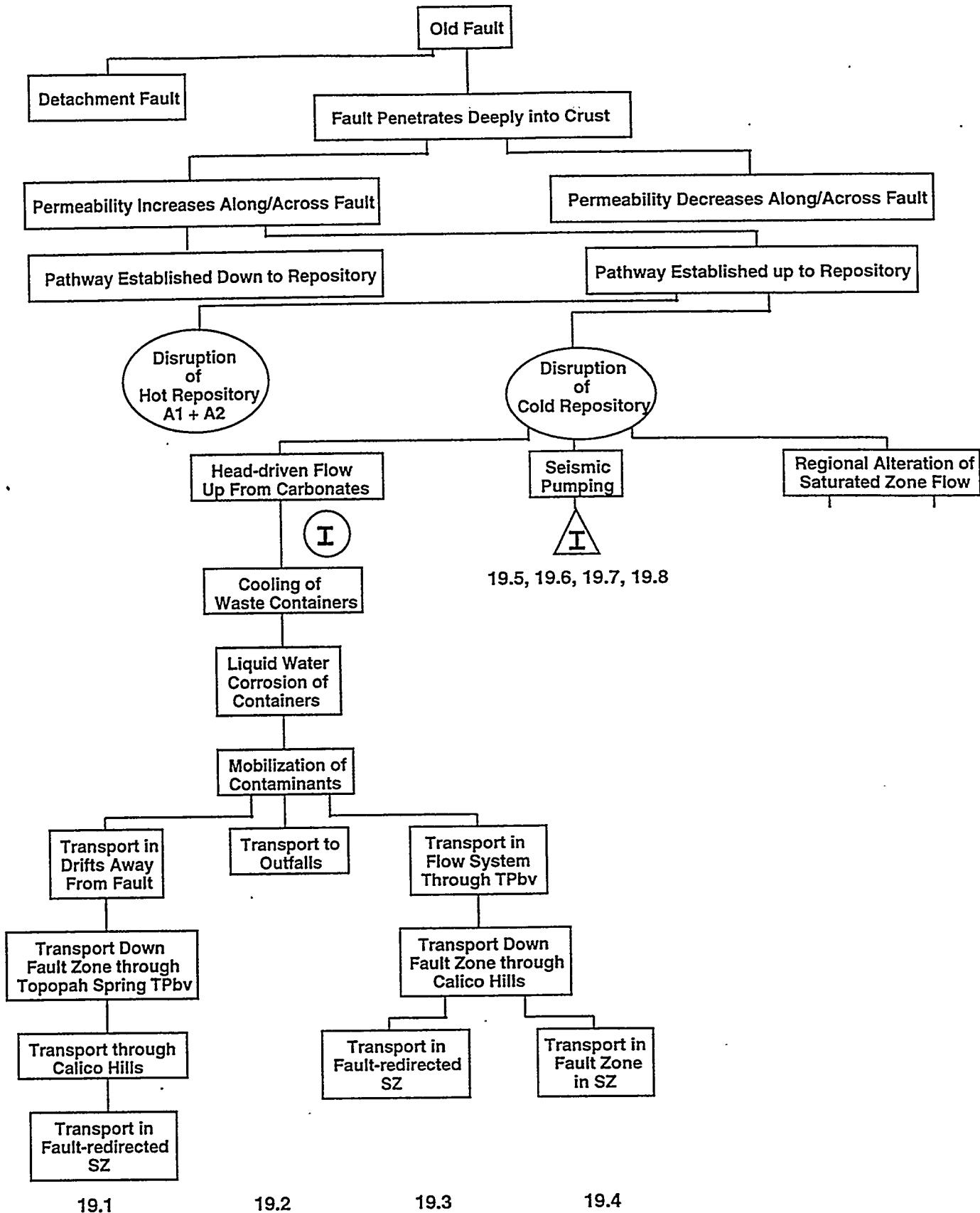


Figure 40. Tree Segment 19, Paths 19.1-19.8, "Tectonic Processes," "Old Fault," "Fault Penetrates Deeply into Crust," "Permeability Increases Along/Across Fault,"...

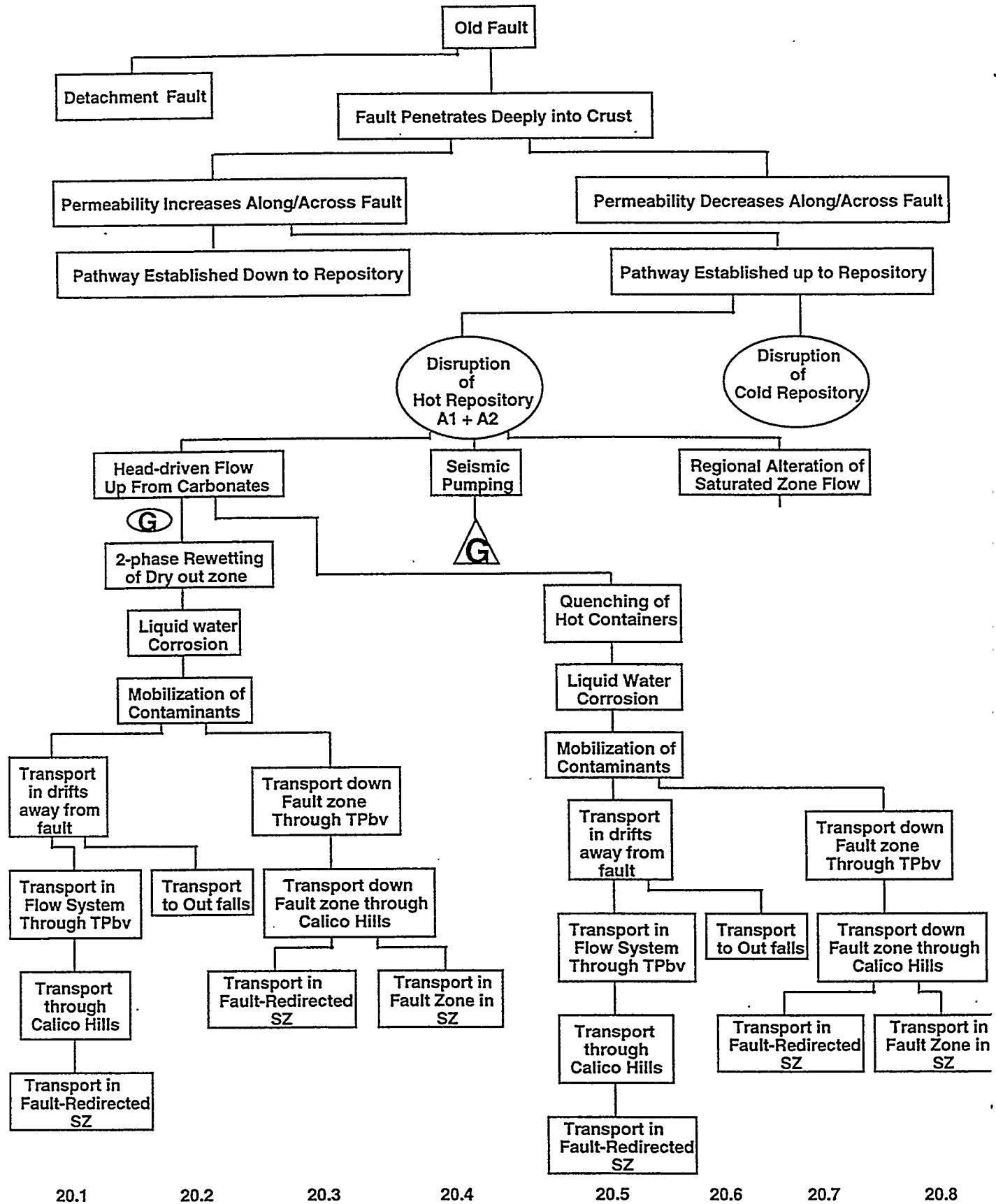
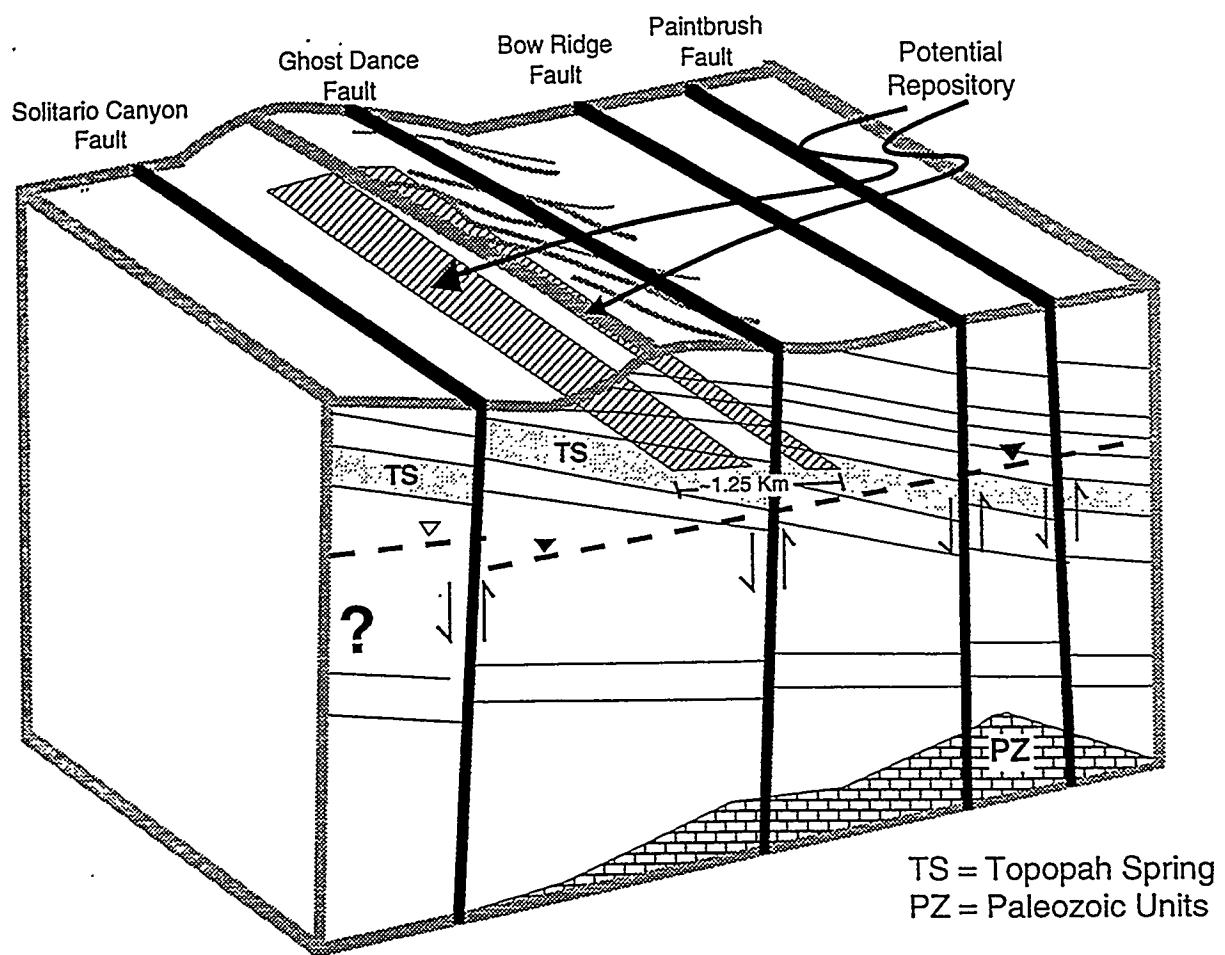


Figure 41. Tree Segment 20, Paths 20.1-20.8, "Tectonic Processes," "Old Fault," "Fault Penetrates Deeply into Crust," "Permeability Increases Along/Across Fault,"..." .



**Figure 42. Tree Segment 21, Paths 21.1-21.3,
 "Tectonic Processes," "Old Fault," "Fault
 Penetrates Deeply into Crust,"
 "Permeability Increases Along/Across
 Fault," ...**

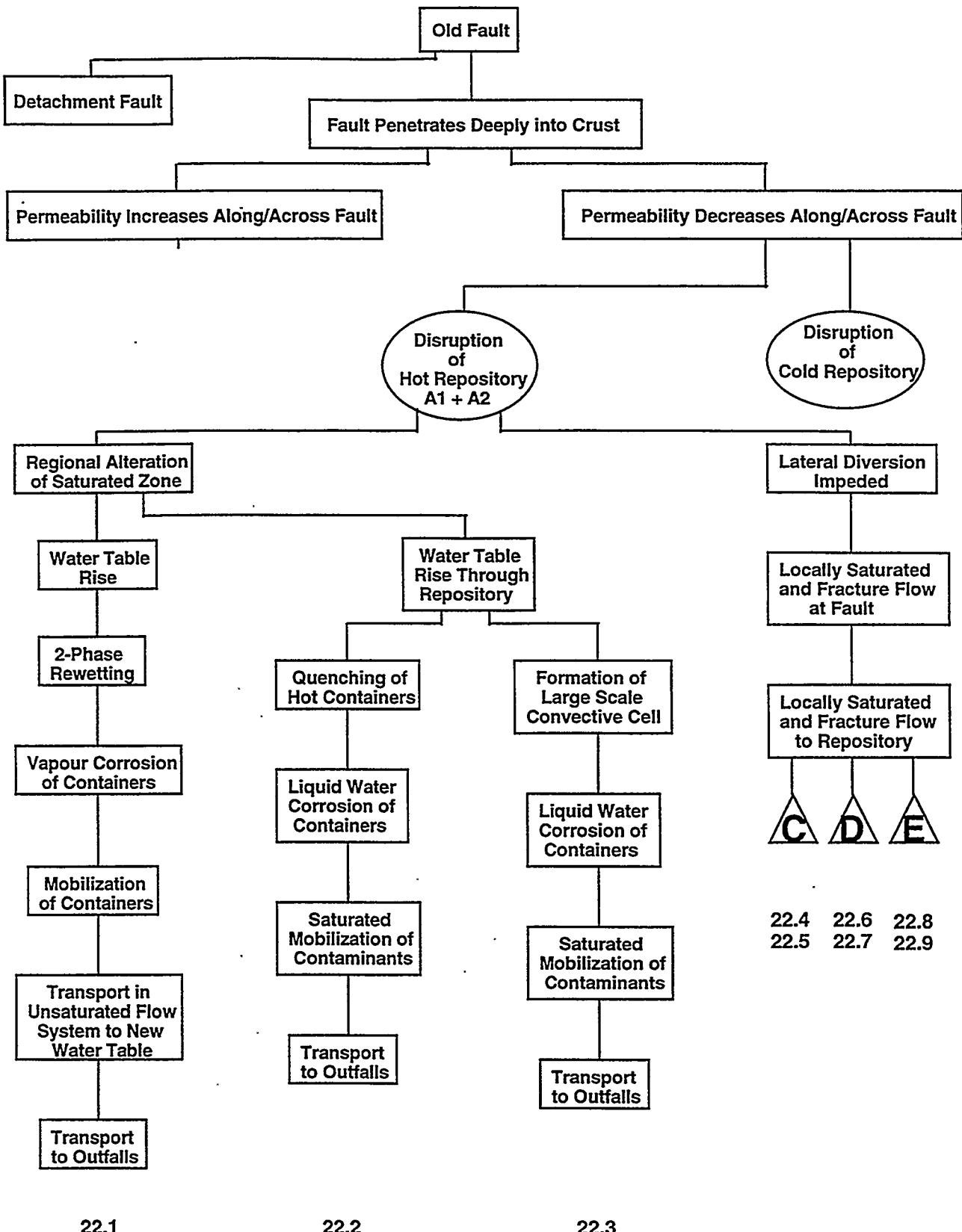


Figure 43. Tree Segment 22, Paths 22.1-22.9, "Tectonic Processes," "Old Fault," "Fault Penetrates Deeply into Crust," "Permeability Decreases Along/Across Fault,"..

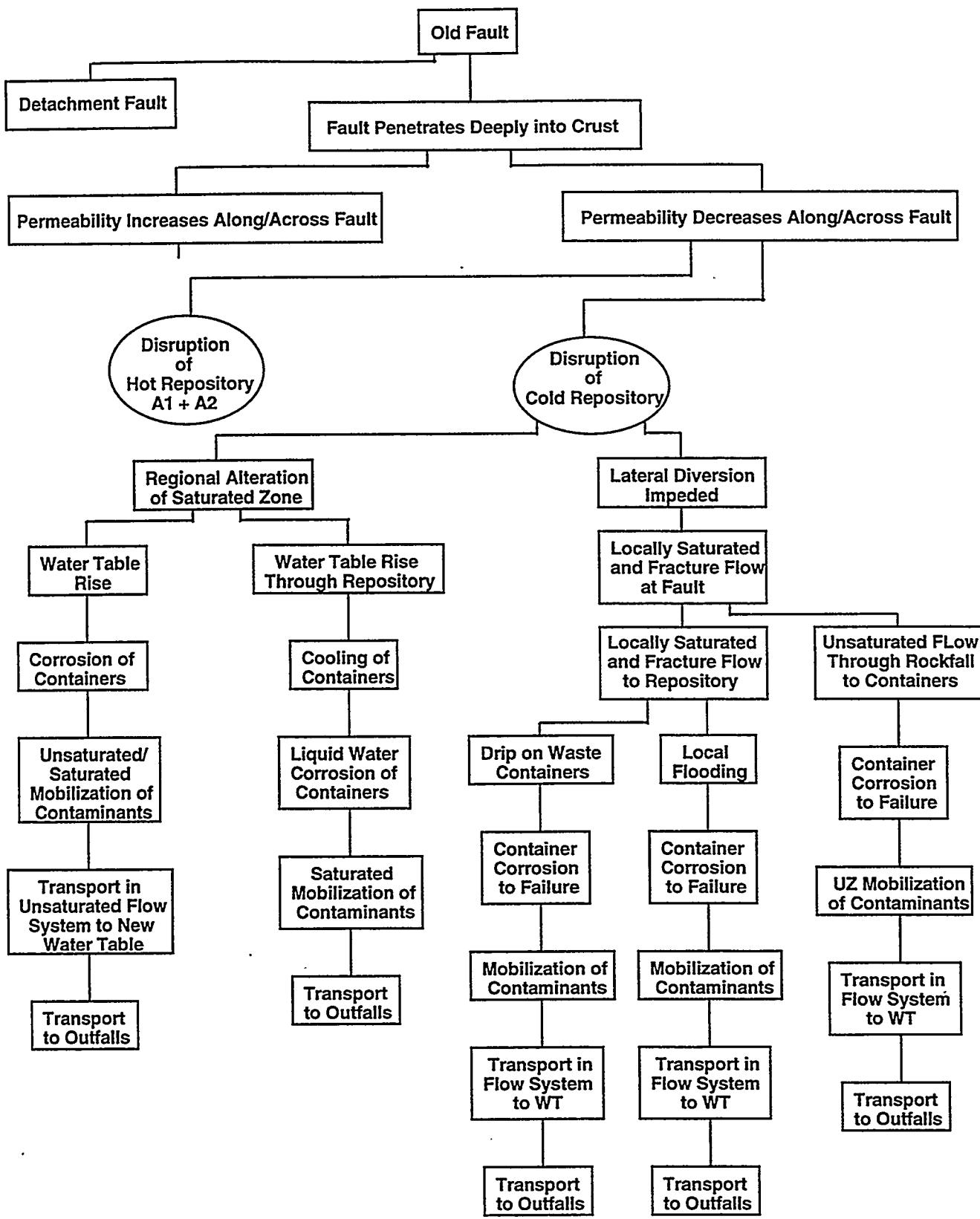


Figure 44. Tree Segment 23, Paths 23.1-23.5, "Tectonic Processes," "Old Fault," "Fault Penetrates Deeply into Crust," "Permeability Decreases Along/Across Fault," ...

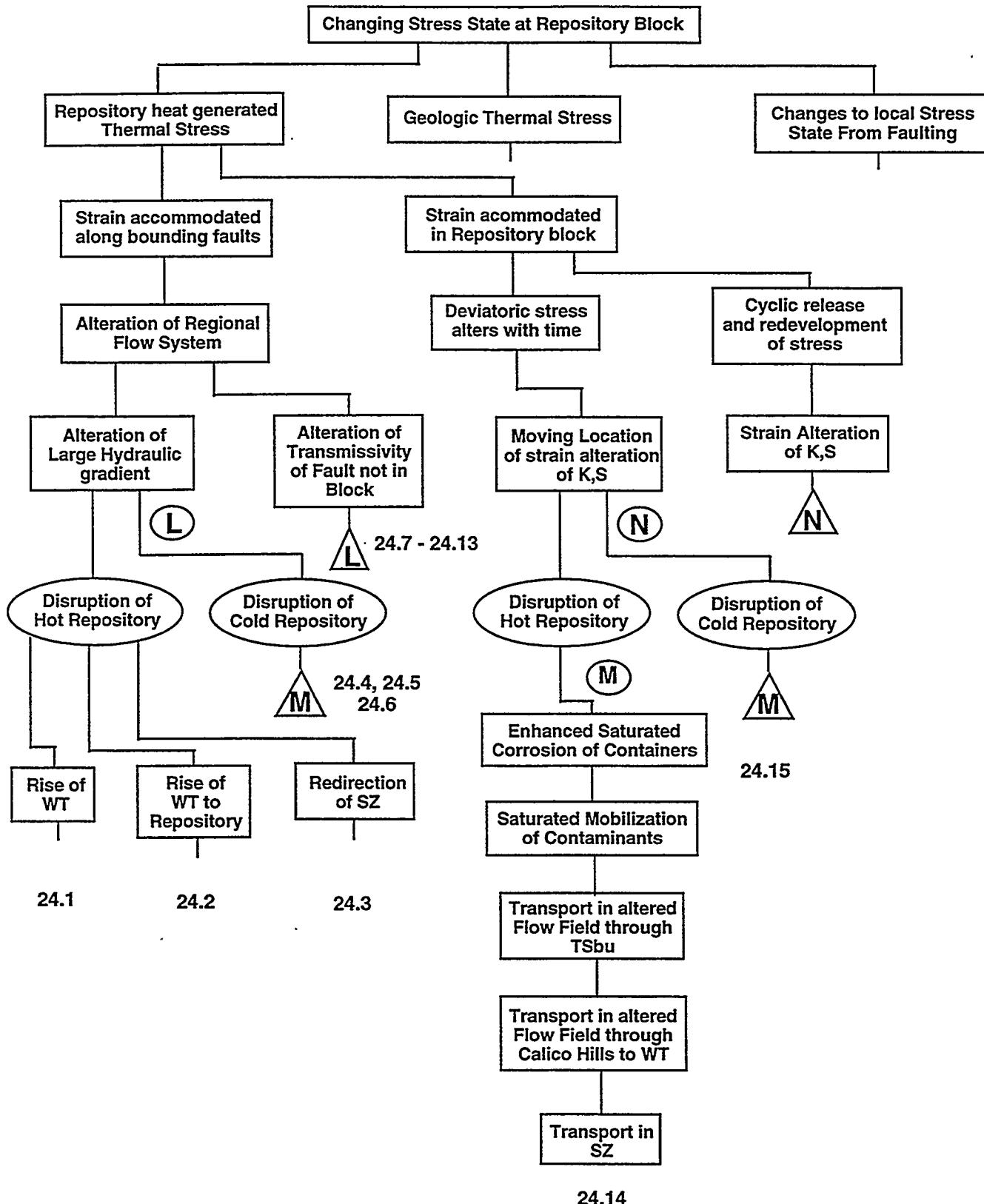


Figure 45. Tree Segment 24, Paths 24.1-24.3, "Tectonic Processes," "Changing Stress State at Repository Block," "Repository-Heat Generated Thermal Stress," ...

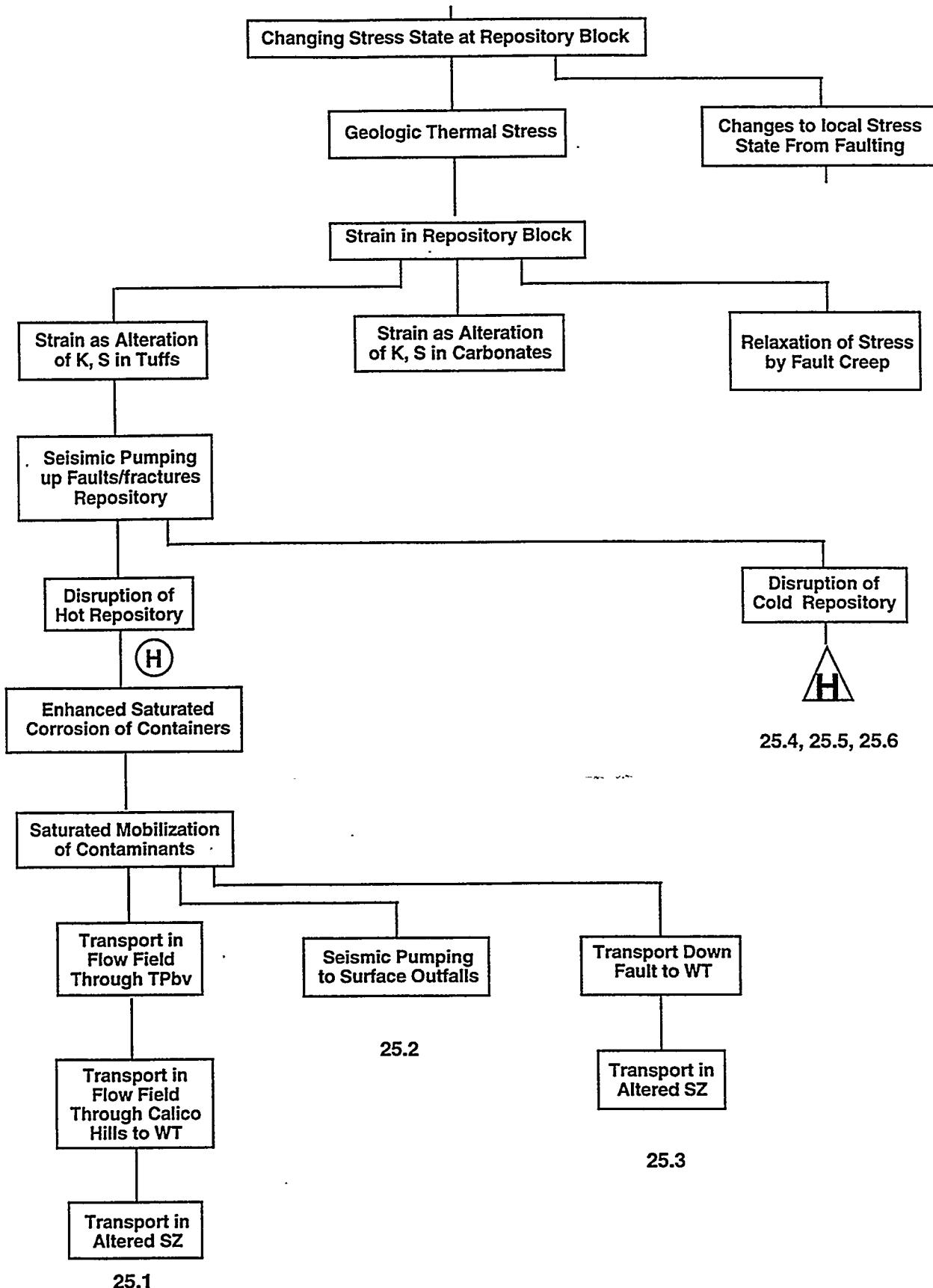


Figure 46. Tree Segment 25, Paths 25.1-25.6, "Tectonic Processes," "Changing Stress State at Repository Block," "Geologic Thermal Stress,..."

(see the section Expected Environment). These alterations may extend below as well as above the repository. The paths 24.14, "Disruption of Hot Repository" and 24.15, "Disruption of Cold Repository" continue with corrosion, mobilization and transport as enhanced by the alterations to the flow field. For "Cyclic Release and Redevelopment of Stress," the idea is that the movement of the stress envelope may produce a stress accumulation to be altered by sudden release as strain. This strain is accommodated by movement on existing, favorably oriented fractures and faults and on new fractures. Essentially, the mountain is generating its own internal mini-earthquakes. The mountain then might be quite noisy as it creaks and groans in adjustment. The process can then redevelop, hence, the idea of a cyclic process. The hydraulic properties of the flow field (K, S, fracture connectivity) also cycle.

Discussion of the section of the tree shown in Figure 46, "Tectonic Processes," "Changes in Stress State at Repository Block," "Geologic Thermal Stress."

This branch, Tree Segment 25, expanded in Figure 46, is intended to recognize that the stress state in the block of rock containing the repository depends, in part, on regional stresses. We expect that the characteristic size of blocks is of the dimension of the spacing for the ranges. Extension and compression have extended over many blocks (Levy and Christie-Blick, 1989). The element "Changing Stress State at Repository Block" is developed into two branches, "Geologic Thermal Stress" and "Changes to Local Stress State from Faulting," forming paths 25,26. Both branches continue with elements concerning adjustments to stress. The branch starting from "Geologic Thermal Stress" is actually intended to include a special problem - the Szymanski scenario (Szymanski, 1989). Szymanski's idea is that the geologic thermal gradient in this region produces thermal expansion and uplift in the rock. Thermal expansion causes a water table drop. Thermal stresses are relieved by an earthquake in or off the block, producing seismic pumping of fluids. This seismic pumping pushes fluids to the repository and by Szymanski's arguments, to the surface. The processes then occur cyclically as the rock reheats and expands. This hypothesis is not supported by current interpretations of various isotopic data and is considered to be incorrect on that basis and on the basis of analyses of seismic pumping (National Research Council, 1992; Carrigan and others, 1991). It is included here as a possible scenario for several reasons: for completeness, as a demonstration of the possible subtlety of coupling of the repository with processes originating at depth, and as a place holder in the tree for other currently unsuspected couplings involving stress changes occurring away from the repository block.

Paths 25.1-25.3 continue with "Strain in the Repository Block" described as either "Strain as Alteration of K(hydraulic conductivity) and S(storativity) in the Tuffs" and "Strain as Alteration of K,S in the Carbonates." The two branches, paths 25.1-25.6 and paths 26.1-26.6, are parallel and reflect the fact that we don't know how such strain would be distributed as a function of depth. The response to this strain is "Seismic Pumping up Faults /Fractures to Repository," meaning up faults and fractures which intersect the repository. Movement up faults is our only choice here because calculations indicate that even substantial earthquakes produce limited general rise of the water table (Carrigan and others, 1991; Arnold, 1996). The fluid arrives at a disrupted repository in "Disruption of Hot Repository," "Disruption of Cold Repository." If the earthquake did not involve a

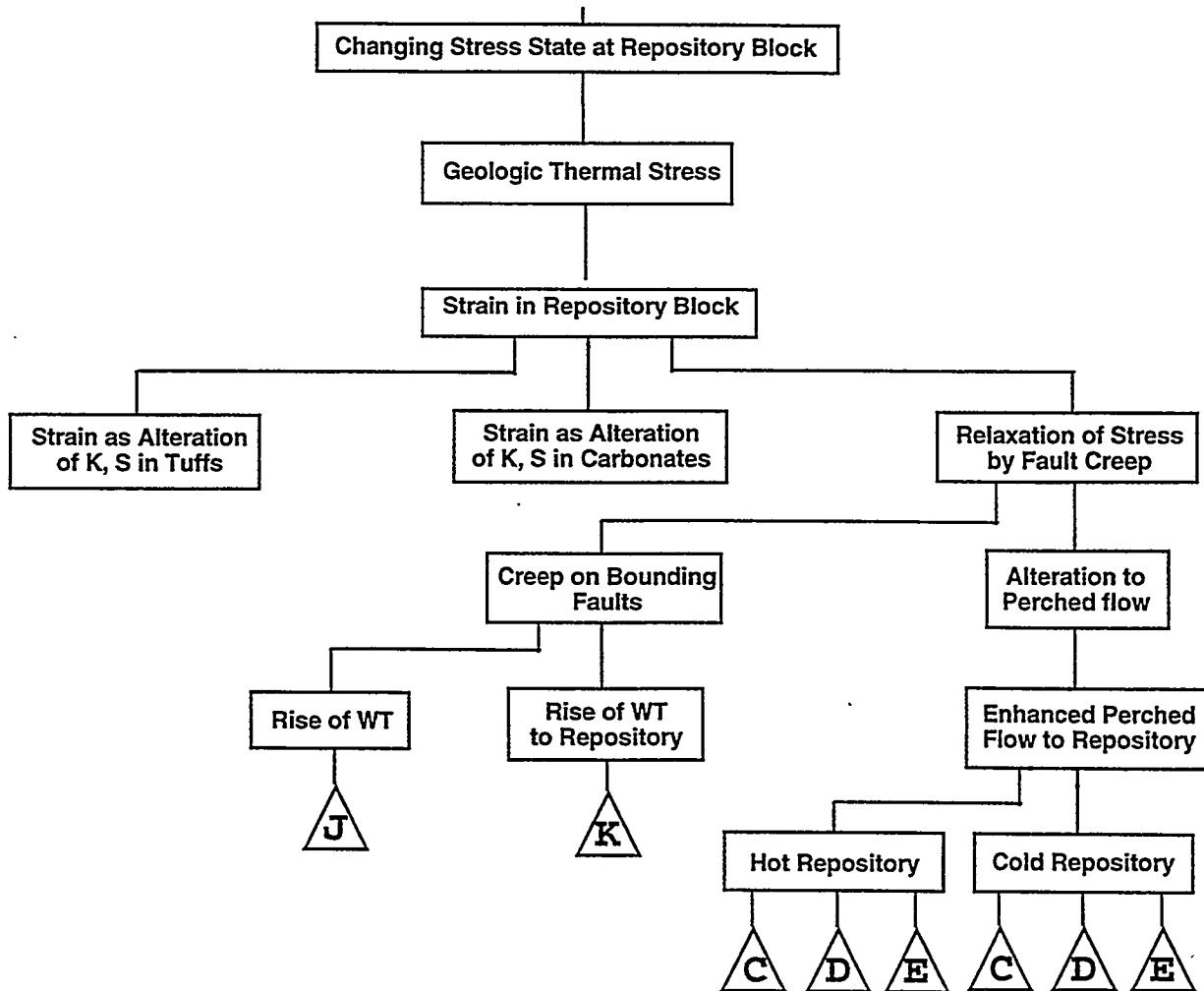
not involve a fault through the repository block, then the disruption is probably limited to increased and generally distributed rock fall and container damage, with some alteration of the flow system to the repository. If fluid were to be pumped up from depth it is likely that its temperature and chemistry would differ from that around the repository; accordingly, the element "Enhanced Saturated Corrosion of Containers" is included. The more likely circumstance of a small rise of water table which does not reach the repository is ignored (Carrigan and others, 1991; Arnold, 1996). The fluids are more likely to be characteristic of tuffs or carbonates and the situation to be similar to that of several of the seismic pumping scenarios considered earlier in "New Faults" and "Old Faults." The real exception is the idea of recurrence, which is an unknown possibility at present.

We continue with "Saturated Mobilization of Contaminants" on the assumption that water pouring up the faults (or fractures) mobilizes the contaminants and carries them down the drifts to be "Transported in the Flow Field Through the Topopah Spring Basal Vitrophyre"; to be transported to surface outfalls by the flow generated by seismic pumping (the original Szymanski hypothesis) or to be "Transported Down the Fault to the Water Table." The last element describes the possibility that the seismic pumping is of limited duration, so that whatever the volume of water pumped up the faults, it is rapidly drained down the way it entered, carrying contaminants with it. For paths 25.1, 25.3, both end with "Transport in Altered Saturated Zone," since the water table has moved and the head structure has been changed by the seismic pumping.

The paths for the "Disrupted Cold Repository" are similar, to those discussed earlier with the obvious changes to the saturated zone elements, so we will spare the reader.

Relaxation of Stress by Creep

A possible means of release of the stress accumulated is creep in the fault zone or on fractures, "Relaxation of Stress by Creep," which allows the stress to be relieved by strain but without catastrophic movement. Tree Segment 26 examines a number of branches dependent on this mode (Figure 47). The first set of branches consider that the "Creep Occurs on Bounding Faults." A particular case of this is the circumstance that thermal expansion of the mountain, due to the hot repository, is adjusted along the Solitario Canyon Fault or the Bow Ridge Fault. Calculations for an thermo-elastic mountain (Jung and others, 1994) indicate that the top will rise about a foot in 300 years. There is some differential expansion due to different units and different amounts of overburden, depending on geographical location. It is possible that the mountain arches in response, resulting in creep along these faults (we have assumed that sudden release is included in other places in the tree). Since upwelling has been identified as occurring in parts of these faults (Sass and others, 1988), a possible consequence is a change in vertical transmissivity, causing a rise in the water table. Such changes are identified in the branches below "Creep on Bounding Faults" as "Rise of WT" and "Rise of WT to the



26.1 - 26.12

Figure 47. Tree Segment 26, Paths 26.1-26.12, "Tectonic Processes," "Regional Coupling," Regional Fault Movement,"...

Repository." The remainder of the branches continue as did earlier branches concerned with water table rise. We have not been more specific about whether the fault transmissivity increases or decreases because either could produce the rise depending on which fault's transmissivity is altered. The "Relaxation of Stress by Creep" could also be distributed on fractures throughout the mountain. A possible change affecting the flow to the repository is "Alteration to Perched Flow" where opening and closing fractures alters fracture transmissivity and yields "Enhanced Perched Flow to the Repository." These branches continue as did earlier branches with "Hot Repository" and "Cold Repository." In these cases, disruption is limited to the changes in fracture transmissivity above and below the repository as they are superimposed on the existing flow system. Those details are available elsewhere in the text.

5.4 Regional Coupling

Discussion of the Tree Segment 27, Tectonic Processes, Regional Coupling

The final branch "Regional Coupling" is seen in Figure 48. It has two sets of branches to address "Remote Seismic Events" and "Regional Fault Movement." "Remote Seismic Events" is intended to describe ongoing seismic activity occurring off the block that produces ground motion in the repository sufficient to damage containers or waste or to alter the flow field. Response of the water table in this region to remote earthquakes indicates rapid rise or fall of a few meters and a more gradual decay to the original water table (Lehman and Brown, 1995). This response does not indicate any durable alteration to the flow field and will therefore be ignored here. The more likely disruption of the repository, hot or cold, is increased rock fall in the drifts. The Tree Segment then continues by reference to earlier discussions in the usual way. The changes are restricted to rock fall as a disruption to containers and as a disruption to the flow field extant at the repository.

The last branch, "Regional Fault Movement" addresses structural movement off block that significantly alters the regional flow system, "Regional Saturated Flow Altered." The branch is developed with a particular alteration in mind. That is alteration to the large hydraulic gradient region to the north of the repository. The large hydraulic gradient has been suggested to be the consequence of structural controls (Fridrich and others, 1994a). The durability of these controls is not known and is under investigation. If the large hydraulic gradient is not durable against regional seismic activity, there is a possibility that the higher water table to the north could move south, reducing its distance below the repository or flooding it. Currently, there is no evidence available that is interpreted as supporting migration of the large hydraulic gradient. As suggested in Fridrich and others (1994a), the large hydraulic gradient at Yucca Mountain seems to be part of a more extensive region with this feature. This branch continues with "Rise of WT" and "Rise of WT to the Repository" and follows the usual development of such branches.

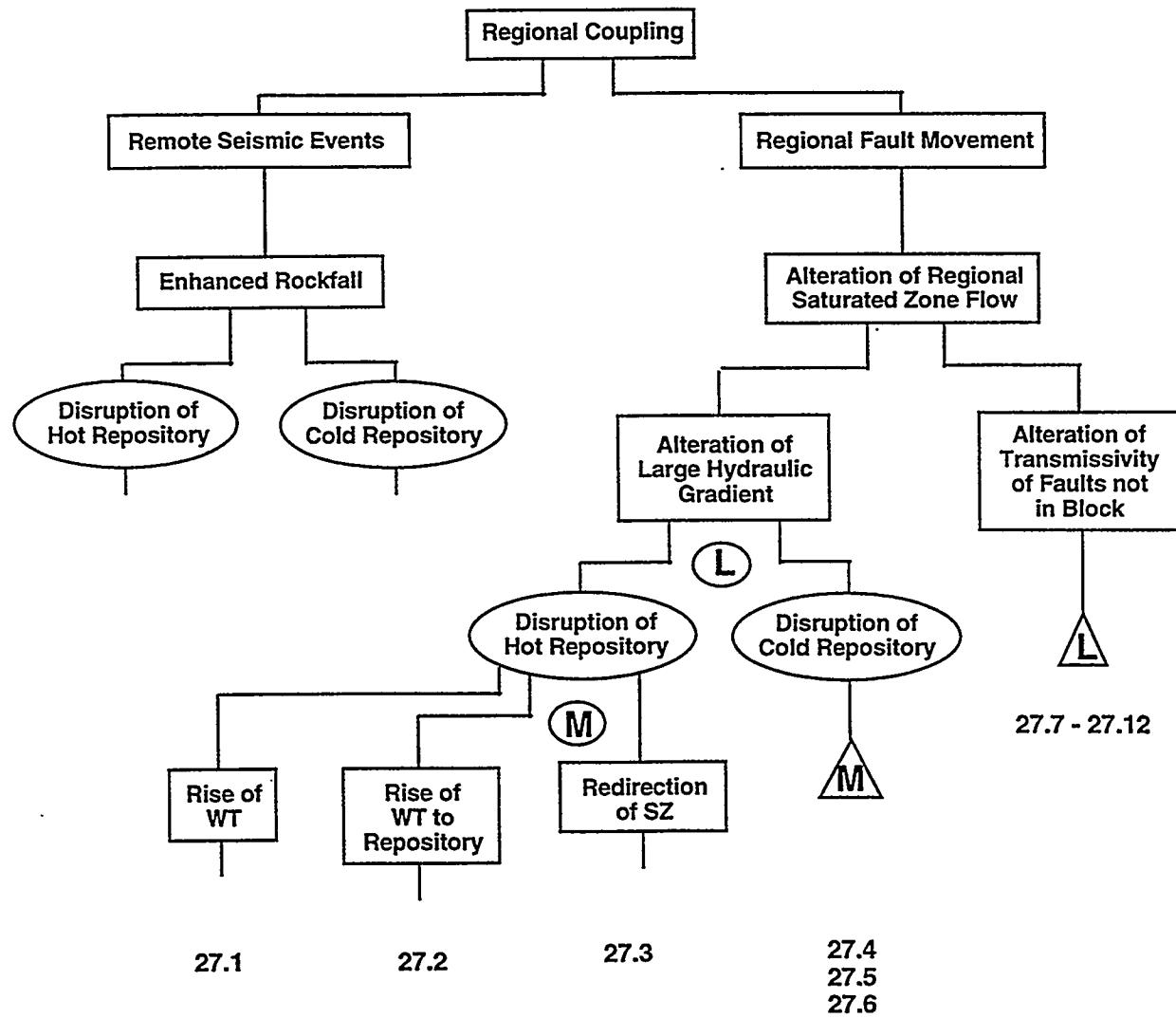


Figure 48. Tree Segment 27, Paths 27.1-27.12, "Tectonic Processes," "Regional Coupling," "Regional Fault Movement," ...

6.0 OPEN ISSUES

There are a number of issues left open or left unmentioned in the text, which affect the relative importance of scenarios and their inclusion or exclusion. We enumerate these issues which we think have arisen in the course of development of the text, for which further data and analyses would be necessary to establish their importance. We specifically discuss one of these issues, Perched Water, at some length because new information derived from site characterization while this document was being prepared, raise its importance even though understanding is still too immature to easily include it in scenarios. It points to the level of understanding one might expect for the other open issues. We expect that there are additional issues we have omitted which the reader will identify.

6.1 Conceptual Model of Faulting

Geologic field studies to characterize the magnitudes, recurrence rates, and styles of faulting and related tectonic deformation at Yucca Mountain are nearly complete. A current major gap in these studies is development of a conceptual model of faulting in the Yucca Mountain region that is specifically tailored to form the basis for hydrologic and engineering characterizations of the faults, including the magnitude and nature of deformation, and the resulting changes in rock properties that are anticipated in a single faulting event. The discussion of this topic earlier in the text emphasized the preliminary nature of the current interpretations.

6.2 Perched Water

Recent drilling and testing results have shown perched water to possibly be common in the immediate vicinity of, but below the horizon of the potential repository under Yucca Mountain. The following discussion, which is much more extensive than the brief comments offered about other open issues, will provide a summary of our tentative understanding of the perched water and then present some possible consequences to indicate why this issue needs to be vigorously pursued in future site characterization efforts. The principal potential problems that perched water might pose involve interactions with thermal loading, and response to climate change and tectonic events, alone or severally. Since the data and interpretations are new, scenarios involving perched water were not discussed in the document describing construction of scenarios associated with the nominal flow system (Barr and others, 1995). Detailed inclusion of perched water in scenarios is necessary to provide perspective on its importance to the repository system. Pending such inclusion, the focus here is on effects clearly associated with tectonic events and processes.

Until recently, perched water has been considered to be rare or possibly absent under Yucca Mountain because of the very low infiltration rate at this site (DOE, 1988). A conceptual model of the unsaturated zone by Montazer and Wilson (1984) envisioned only temporary and minor development of perched water bodies. Perched water was first

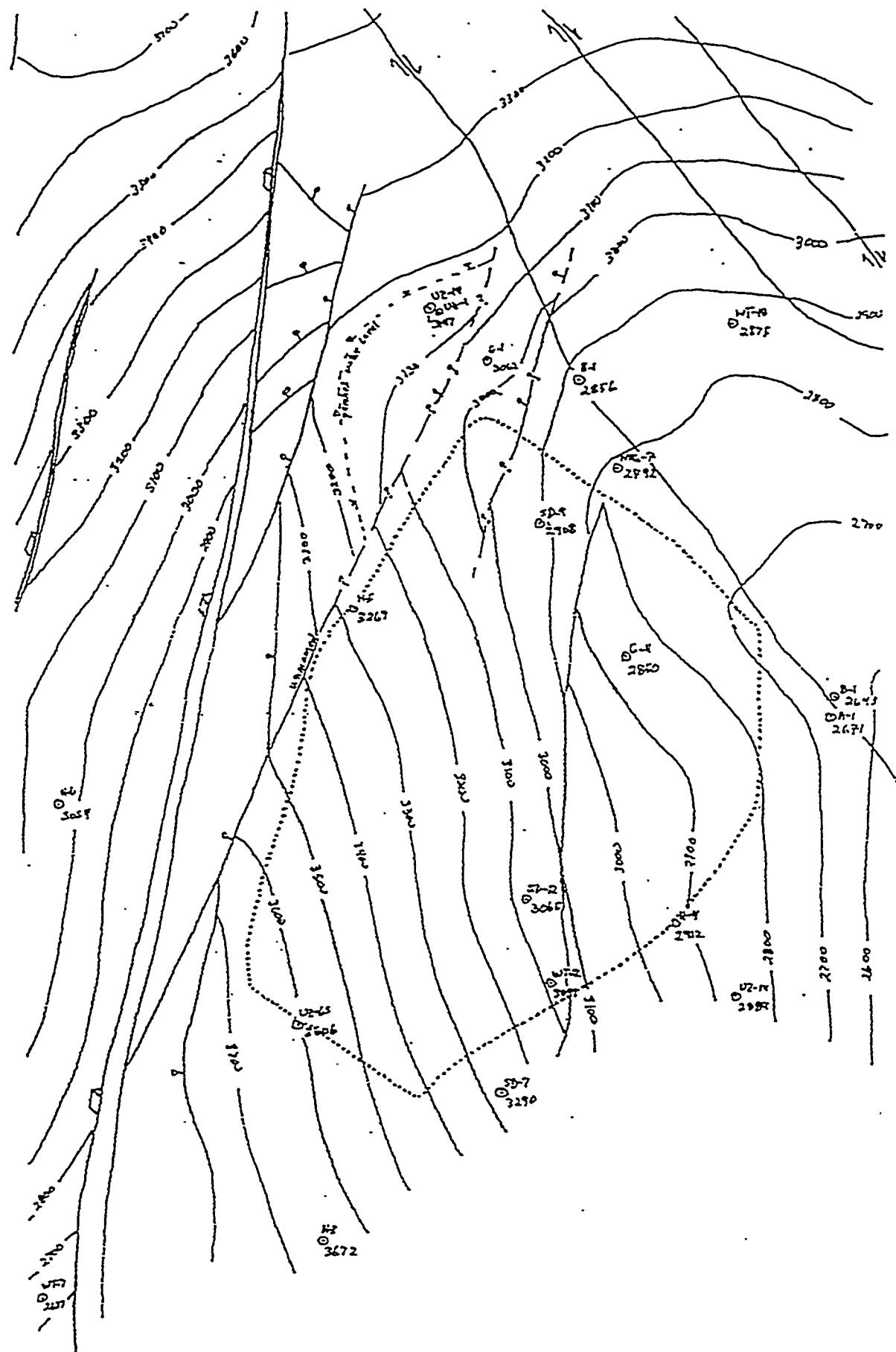


Figure 49. Structure map at the level of the lower bounding horizon of the perched water body in wells USW UZ-1 and USW UZ-14. Taken from work in progress (1996) by C.Fridrich and others, US Geological Survey.

discovered under Yucca Mountain in 1983 during the drilling of bore hole USW UZ-1, located about 500m north of the northernmost tip of the potential repository area (Figure 49). Due, however, to the presence of drilling polymer in recovered water samples, it was concluded that the water in USW UZ-1 probably was an "unnatural" perched body created by loss of drilling fluid from an earlier drill hole (Whitfield, 1985; Water, Waste, and Land, 1986).

In 1994, USW UZ-1 was replaced by a new well, USW UZ-14, which was drilled about 30m to the northwest (Figure 49). USW UZ-14 found the same perched water body with the same water level (966m asl) as was found in USW UZ-1, according to R. R. Luckey, USGS. Extensive pumping, sampling, and analysis of the perched water from USW UZ-14 has shown the presence of some contamination by lost drilling fluids. However, the water is much younger in apparent carbon-isotope age and much less evolved chemically than any of the waters that were used in drilling previous holes at Yucca Mountain; according to W. Steinkampf and Z. Peterman, USGS, it is a natural perched water body apparently derived from downward percolating waters (or lateral flow from a nearby recharge area). A structure map (Figure 49) generated at the level of the lower bounding horizon of the perched water body in wells USW UZ-1 and USW UZ-14 shows that this body may cover an area as large as 100 acres, and may extend to within 100m of the potential repository outline.

Subsequent to the drilling of USW UZ-14, perched water has been found in all four of the holes that have been drilled "dry" within or immediately adjacent to the potential repository area under Yucca Mountain, namely USW NRG-7/7a, USW SD-7, USW SD-9, and USW SD-12 (Figure 49), according to R. R. Luckey, USGS. Perched water was not found in several previously drilled holes, in the same area, such as USW G-1, USW H-1, and USW H-4. However, given that these previous holes were drilled with water, and given the low permeability of some of the perched horizons in the more recent holes, it is possible that perched water went undetected in these previously drilled holes. It is therefore possible, but unproven, that perched water is ubiquitous in the potential repository area.

In USW UZ-1 and USW UZ-14, the perched water is found in the lowermost part of the repository horizon, the densely welded and devitrified crystallized subunit of the Topopah Spring Tuff. The rock unit that apparently creates the hydraulic barrier to downward percolation is the underlying basal vitrophyre (dense glass) of the Topopah Spring Tuff, in which the fractures were found to be plugged with smectitic clays, breakdown products of the volcanic glass. In addition, there must be a lateral barrier to flow that separates wells USW UZ-1 and USW UZ-14 from well USW G-1 (Water, Waste, and Land, 1986). This lateral barrier may be a northeast-trending fault that does not extend this far to the northeast on the surface, but that has been shown to be a growth fault in the Paintbrush volcanic section, meaning that it is larger and more extensive at depth than it is on the surface (according to Day and others, 1995; Scott and Bonk, 1984).

In the other four wells in which perched water has been found, the level of perching is either in the same stratigraphic interval (1 well) or in the underlying Calico Hills Formation, a sequence of glassy, nonwelded bedded tuffs that is variably zeolitically

altered. Laterally, the glass/zeolite boundary within the Calico Hills Formation cuts across stratigraphy from the upper to the middle part of the unit. In each well that has perched water in the Calico Hills Formation, it is located just above that boundary. In all six wells in which perched water was detected, water was found immediately over horizons in which volcanic glass has been altered, reducing the primary permeability and forming the hydraulic barrier above which water is perched.

In the SD and NRG drill holes, there is no evident lateral barrier to flow; however, these wells also lack the thick columns of perched saturation found in the two UZ holes. It is possible that the perched water in the SD and NRG holes represents a thin, broad layer of perched sheet flow that is leaking down-structure (Figure 49) along the inclined hydraulic barrier from the major perched body in the vicinity of the two UZ holes.

The impact of tectonic processes seems to occur in three major ways. First, a tectonic event could create new fracture paths through the altered Topopah Spring basal vitrophyre. The alterations suggested by Wm. Glassley, LLNL, as occurring to this basal vitrophyre during the repository thermal period include alteration of glasses to clays and zeolites, accompanied by a volume increase. These changes may fill and plug fractures and divert flow along the top of the altered region. The expected effect on contaminant transport is to lengthen the residence time for contaminants moving through this unit. Transmissive new fractures would short circuit the flow. If the tectonic event occurred early enough, before the repository thermal period is over, then there is opportunity for such paths to heal. When the tectonic event occurs, it becomes an important element in constructing scenarios.

Second, a tectonic event could change permeabilities and therefore travel times along infiltration pathways. Current infiltration has some residence time to arrive at the horizon of the potential repository. Reduction of that travel time alters the response of the repository, a concern under present climate conditions and perhaps a more serious one under a wetter climate.

Third, a perched water body is in some kind of equilibrium with its source and its drain, whether its volume is increasing, decreasing or static. A tectonic event could alter connection of the perched water body below the repository horizon to its source and redirect that water to or closer to the repository. A tectonic event could alter connection of the perched water body below the repository to its drain, perhaps reducing the effectiveness of the drain. Perched water could then accumulate, providing a source of water closer to the repository for interaction with repository heat or it could find a new drain close enough to the repository to participate in the flow system responsible for contaminant transport.

In spite of the work discussed here, this remains an open issue. In the absence of perched water being exhaustively included in scenarios, it is somewhat difficult to anticipate how else the flow system will be affected. Clearly, scenarios for the nominal flow system need to be reexamined with the new data on perched water in mind, particularly with respect to the thermal effects of and on the repository in order to better set the scene for

what features or processes tectonic events will change. The remainder of the open issues will be mentioned only briefly.

6.3 Large Hydraulic Gradient

An important concern is the durability of the large hydraulic gradient (LHG) in response to seismic activity. The threat to the potential repository site is substantial elevation of the water table. Resolution of the response of the LHG to seismic activity requires a good understanding of its hydrogeologic controls (Sinton, 1989), which presumably means that data need to be collected and analyzed. However, examination of the geologic record indicates that this has not happened in the past (Levy, 1991).⁵

6.4 Carbonates - Head Distribution

If the Carbonate aquifer systems are coupled to the tuff systems or are to be coupled because of seismic activity, then the current potentiometric surface in the carbonates and the hydrologic properties of the carbonate aquifer need to be established. Such coupling suggests the possibility of current long residence times in the tuff aquifer. Alteration of the coupling could reduce residence times and establish new pathways. The issue is partly resolvable by data.

6.5 Deeper Flow Systems? - Disruption

Faulting, other than movement on shallow listric faults, is likely to disrupt any deeper flow systems, that is, flow systems below the carbonates. We know of no data showing that such systems exist or have any potential for affecting a repository at Yucca Mountain, but the issue is not dismissed out of hand. Probably the Sr isotopic work of the USGS offers the best chance of dismissing this issue.

6.6 Container Damage from Rock Fall

a. Mechanical

Rock fall on to the container is likely to cause stress damage and punctures which affect integrity and containment (St. John and Mitchell, 1987). It would be most useful to be able to relate time after emplacement, that is in effect temperature, to the sensitivity of rock fall for seismic events. This would establish, roughly, the history of rock fall in the repository.

⁵ Marshall, B. D., J. S. Stuckless, Z. E. Peterman, and J. F. Whelan, 1993. "Isotopic Studies of Cavity Filling and Fracture Coating Minerals as an Aid to Understanding Paleohydrology," Yucca Mountain, NV, Nuclear Engineering Agency Proceedings for a Workshop on Paleohydrologic Methods and Their Application for Radioactive Waste Disposal, pp. 147-159.

b. Thermal

Substantial rock fall which covers containers is likely to insulate them and produce higher container temperatures and reduce repository driven hydrothermal flows. Some means of deriving the changes to the hydrothermal flows is necessary to assess the importance of scenarios involving them.

6.7 Backfill?

No decision has yet been made about the use of backfill around waste containers. Its presence or absence alters the repository-driven, hydrothermal flow systems and reduces the vulnerability of containers to rock fall.

6.8 Fault Controls on Current Flow System - (e.g., Solitario Canyon Fault, Drill Hole Wash Structure, Yucca Fault, Bow Ridge Fault)

Work by the USGS on water table temperatures indicates some upwelling from the carbonate aquifer systems to the tuffs at places along Solitario Canyon Fault and Bow Ridge Fault (Sass and others, 1988). Attempts to construct limited 3-Dimensional models of the saturated zone around Yucca Mountain suggest that faults may control the flow system (Wilson and others, 1995). This raises the issue of how durable those controls are in the face of seismic activity. The answer is partly available from known responses to recent California and Nevada earthquakes, but more detailed study at these faults would be helpful.

6.9 Coupling Between Basaltic Volcanism and Faulting

The relation between the processes producing magmatism and causing faulting in this area is an open question being currently studied (see for example, Meyer and Foland, 1991; Fridrich and others, 1994b, and US Geological Survey, 1994). Resolution of their connection determines whether they can be treated as separate or as dependent processes and is an important element in assessment of the long-term performance of the potential repository.

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