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Scenarios Constructed for Basaltic Igneous Activity at Yucca Mountain and Vicinity

G. E. Barr
E. Dunn
H. Dockery
R. Barnard
Sandia National Laboratories
Albuquerque, NM
and
G. Valentine
B. Crowe
Los Alamos National Laboratory
Los Alamos, NM

ABSTRACT

The Yucca Mountain Site Characterization Project (YMP) will model the behavior of a potential repository system. To do so, it is developing scenarios for the release of radionuclides. The scenario-development effort has defined a "scenario" as a well-posed problem connecting an initiating event with radionuclide release to the accessible environment by a logical and physically possible combination or sequence of features, events, and processes (FEPs). Drawing on the advice and assistance of YMP principal investigators (PIs), a collection of release scenarios initiated by basaltic igneous activity* occurring in the vicinity of the potential repository is developed and described in pictorial form. A summary of open issues that may require further study is appended to the collection of scenarios. It is intended that this collection will provide a framework to assist PIs in recognizing essential field and calculational analyses and to assist performance assessment in recognizing what analyses remain before preparation for the Nuclear Regulatory Commission (NRC) license application is complete.

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* Throughout this report we refer to basaltic igneous activity, including both intrusive and extrusive expressions, as basaltic volcanism.

The work in this report was performed under WBS 1.2.1.4.1

The data in this report was developed subject to QA controls in QAGR S12141A, Revision 0, PCA 2.0, Task 2.2; the data is not qualified and therefore can not be used for licensing

Acknowledgments

Leo Gabaldon of Tech Reps created the illustrations for this document. A picture can effectively communicate much that is difficult to put into words. Leo had the perfect combination of training, skills, talent, initiative, yin and yang to express in picture each concept presented to him. Several of the illustrations pointed out--to the authors--details we had not yet considered. You will notice Leo's penchant for perfection by the detail in his work. We appreciated Leo's dedicated effort and his unique combination of abilities.

Jeanette Anderson of Creative Computer Services produced the event tree for this document. We appreciate the diligent care and effort required to maintain accuracy and presentability.

The authors wish to thank Dave Borns, Chris Rautman, and Felton Bingham whose thoughtful comments and suggestions for changes improved the quality and completeness of this document.

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Introduction

Basaltic volcanism has been identified as a possible future event initiating a release of radionuclides from a potential repository at the proposed Yucca Mountain high-level waste repository site. The performance assessment method set forth 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 catalogue the details of the interactions between the features and processes produced by basaltic volcanism in the presence of the presumed groundwater flow system and a repository structure, the engineered barrier system (EBS), and waste. This catalogue is developed in the form of scenarios. We define a scenario as a well-posed problem, starting from an initiating event or process and proceeding through a logically connected and physically possible combination or sequence of features, events, and processes (FEPs) to the release of contaminants.

To construct a complete and exhaustive catalogue of release scenarios would require a synthesis of all currently available information, geologic and hydrogeologic as well as of engineered components, repository, EBS, and waste. Completeness in this sense 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. To help guide future studies, we include at the end of this report a summary of the open issues we identified: i.e., of the technical information that may require further investigation.

To organize the information, interpretations, and speculations, all generously provided by many project PIs, we chose a logical structure that we call an event tree.* The event tree is used to systematically organize FEPs and the understanding that investigators have of these phenomena. The event tree is then used as a tool for systematic construction of scenarios. This particular structure is organized the way PIs think about laying out their problems; a single continuous path through the tree is a scenario and should provide a well-posed problem. To clarify some of these processes, a series of cartoons and sketches supplements the verbal description of concepts. Each cartoon suggests details of possible consequence. To the extent of our knowledge, we have included current results obtained by participants in the YMP. A copy of the reference basaltic volcanism event tree is appended to this report.

Identification of a scenario presumes no knowledge of its probability of occurrence, but rather 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 which are physically impossible will be based upon observations, calculations, and experiments. We expect that the syntheses that produced these scenarios will induce PIs to suggest revisions and omissions both of scenarios and of the organization of FEPs.

We expect frequent revision of the catalogue of scenarios. In particular we note three opportune times for such a catalogue to be reexamined and revised: when site characterization surface-based testing information is available; when entrance to the underground workings is available and incorrect presumptions about the behavior of the site can be corrected; and

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* Since we are dealing with features and processes as well as events, our event trees are generalizations of the event tree concept.

at decommissioning, when 30-50 years of operational experience will have been accumulated. That experience will allow a further elimination of unimportant processes.

Caveats (explanations to avoid misinterpretation)

In both the event tree and this report, arrival of contaminants at the water table is taken to be the release, rather than arrival at the accessible environment as legally defined. This is not to disclaim the saturated zone, but to avoid adding the FEP Transport in the Saturated Zone to the Accessible Environment to most paths. This allows us to focus on details unique to distinct scenarios, including details of the saturated zone only when the standard model of the saturated zone will not apply because of a change or different event in the system.

In addition to the zone below the water table, we use "saturated" or "locally saturated" to refer to a region within the unsaturated zone but with pore space full of water.

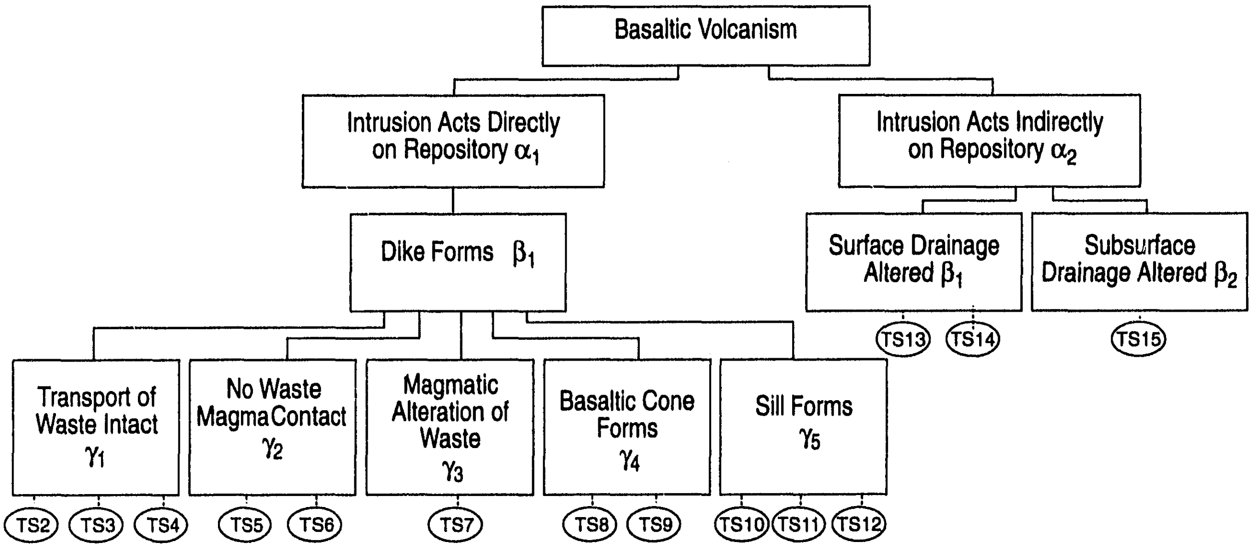
Construction of underground openings causes durable alterations of the rock. There is a stress-altered zone around the drifts and emplacement holes that develops in response to the change in stress when rock is removed. Strains develop to relieve this stress; typically the strains are radial and concentric fractures superimposed on any existing fracture systems. A dike or sill reaching the potential repository must be injected into this stress-altered region. How this affects the behavior of the magmatic flow is currently unknown. We have presumed that the dynamics of injection of a dike will overwhelm any local alterations in the stress field. When field studies are completed on this topic, it will be reconsidered. We have assumed in discussion and particularly in figures that the waste container, waste forms and mode of container emplacement are those of the Site Characterization Plan Conceptual Design Report (SCP-CDR, SNL, 1987). Different modes of emplacement are under preliminary consideration. Our assumption is not intended to preclude other choices. However every change from the reference form requires some reevaluation to see which arguments in the discussion still apply, how figures need to be modified, and what changes are required in modeling. We expect that most of the differences can be addressed as specifics in the detailed modeling of the scenarios.

With one exception we have ignored the thermal state of the potential repository at the time of postulated intrusion, the argument being that the intrusion provides local thermal effects of greater magnitude than does the potential repository. However, the thermal history of the potential repository establishes the initial conditions of the surrounding rock at the time of the intrusion. The matter is thus relegated to modeling. For the exception, Intrusion Acts Indirectly on Repository α_2, a distinction is made between a hot repository and cold repository. During the thermal period of the waste, a relative short period compared to the period of containment, the interactions between the potential repository and the mountain will be fundamentally different from those during the much longer period when the waste is cool. Also, the effects of a hot intrusion are different from the long-term effects associated with the cooled intrusion. Certain transient thermal behavior of the major components may be important.

There is a large body of literature describing the geologic and hydrogeologic setting of Yucca Mountain and vicinity. The Basin and Range province is currently an exciting research area with frequent new publications. While there are, seemingly, contradictions in some interpretations, as for example flow in the saturated zone (Fridrich, et al., 1992, Czarnecki, 1985), substantial further studies are planned or are underway as set forth in the Site Characterization Plan (DOE, 1988). To exhaustively review such new and existing work is beyond the scope of this document. The event trees and resulting scenarios are digests of these data and interpretations. The intent of the scenario documents is to include those interpretations and speculations whose relevance to potential repository success or failure must be resolved and evaluated in terms of radionuclide releases to the accessible environment.

Reading This Report

This report is accompanied by a basaltic-volcanism event tree, located in the back pocket. Frequent reference to this tree may be essential to keeping track of the discussion in the text.



Tree Segment 1. Upper branches of the basaltic volcanism event tree. Ellipses indicate subsequent continuing tree segments located, in numerical order, in the text under basic scenarios.

Tree Segment 1 contains the upper layers of the event tree and provides a structural outline to this report. The ellipse symbols in the lowest tier of Tree Segment 1 are the code to map branches of the event tree found in the text, called Tree Segments, into the complete event tree.

For example (TS2) refers to Tree Segment 2 in the text and to the leftmost branch of Transport of Waste Intact γ_1 in the event tree. Each segment receives discussion in its own section of the text, each of these sections is headed by the title of the segment and the ellipse symbol that denotes it.

The Greek alphabet is also used to facilitate placement of each Tree Segment in the event tree, and to indicate the horizontal levels of the branches being referred to; e.g., the branches directly beneath Basaltic Volcanism are the α layer, and the branches beneath the α layer compose the β layer, etc. A boxed FEP is uniquely designated by its Greek-letter path (e.g., α_i, β_j, γ_k). Specific FEPs are indicated in the text by a change of font; e.g., Intrusion Acts Directly on Repository α_1.

Tree Segments are the figures in the text containing sequences of branches excerpted from the event tree. Each Tree Segment with the exception of Tree Segment 1 consists of two similar figures. (To follow the ensuing explanation, it may be necessary to refer to Tree Segments 2a and 2b on pages 10 and 11). First is Tree Segment #a, which shows a portion of the event tree. A Tree Segment #a caption traces the tree path through preceding FEPs not shown, to the segment depicted; e.g., looking at Tree Segment 1 and the event tree, we see that Tree Segment 2a will have the caption Basaltic Volcanism, Intrusion Acts Directly on Repository α_1, Dike Forms β_1, Transport of Waste Intact γ_1, Waste Transported to Sur-

Table 1: Symbols Used in this Report

Symbol	Usage of symbol
TS#	Symbol for Tree Segment # showing its position in the event tree and in this report
FEP and caption text	Font used when referring to a FEP, Sketch or Tree Segment, and for Sketch and Tree Segment captions.
🅑	Symbol for a group of FEPs that occurs within the dashed box and is repeated elsewhere in the event tree
Ⓑ	Symbol to indicate that the position of the group of FEPs in the above- mentioned dashed box is to be repeated.
➡	A symbol found in Tree Segments that demonstrates the path of a scenario or scenario group through the Tree Segment
→	A symbol that indicates the continuation of a scenario group path from the end of the discussion in the text to the water table
⬟	Symbol and reference number for a scenario path or scenario group path through the event tree
2-1	Symbol indicating where, in a Tree Segment, a Sketch (Sketch 2-1 in this case) first applies to a scenario path

face δ_1. An additional purpose of each caption is to restate the assumptions upon which the discussion of the Tree Segment is based. The second of the similar figures is Tree Segment #b, which shows by a broad arrow symbol, ➡, the paths of scenarios or groups of scenarios discussed from that portion of the event tree. When the discussion ends before the final branches of the scenarios, a narrower arrow symbol, →, shows the continuation of the scenario path to the water table.

Tree Segment #b numbers scenarios or groups of scenarios for ease of referral. Scenarios and groups of scenarios are indicated as broad arrow paths through the Tree Segments and specified in both Tree Segment and text with a numbered pentagon. For example, 2-1 in the text refers to the path in Tree Segment 2b ending in Direct Exposure ε_1.

Some sets of branches are common to more than one path. Each of these sets, when first described, is surrounded by a dashed box and assigned a circled letter; *e.g.*, 🅑. Rather than repeat the entire set of branches at each occurrence, the circled letter in reversed black and white, Ⓑ, serves to indicate the position where the set is replicated. These symbols are summarized in Table 1.

As shown in Tree Segment 1, distinction is first made between an intrusion acting directly upon the potential repository block and one acting indirectly on the potential repository block. Discussion then proceeds to the formation of a dike and five possible categories of interactions of the first molten, then cooling, rock with the potential repository waste. The descriptions of scenarios conclude with the discussion of releases due to altered drainage patterns.

We have represented each scenario with a sequence of Sketches after the fashion of a PI setting up an analysis. Each Sketch illustrates a concept and is possibly distorted in proportion, as a cartoon, to enhance the features of interest, which, if drawn to scale, might not be discernible. Tree Segment #b links Sketches to the concepts discussed by placing the symbol ⇨ containing a sketch number near the FEP the sketch illustrates. We hope that, the combined use of these four components--Event Tree, Tree Segments, Sketches, and text--will reduce ambiguity.

Basic Scenarios

In order to have specific physical and chemical features to discuss in modeling, and to keep the number of scenarios finite, we establish paradigms for emplacement of the deleterious basaltic intrusions. We have chosen two representative settings for paradigms: one with the intrusion through the potential repository (Intrusion Acts Directly on Repository α_1) and one with the intrusion outside the potential repository (Intrusion Acts Indirectly on Repository α_2).

For the direct interaction case, a dike or en echelon dikes are injected through the potential repository in a direction perpendicular (NNE/SSW) to the least principal stress as measured in this area or along preexisting faults with trends that are nearly perpendicular to the least principal stress (e.g., Delaney et al., 1986). It is likely that whatever the direction of injection of the dikes, the near-surface stress field influences their surface expression. Other orientations are not excluded, but are variations. A dike reaching the potential repository depth is presumed to continue to the surface to form fissure eruptions.† Observations at Crater Flats and in Hawaii suggest that such dikes, after a period of eruption, focus to one or more vents, which form cinder cones. Effects of these processes and features are superimposed on the existing hydrologic flow system.

The paradigm dike structures are based on regional studies (Crowe et al., 1983) that indicate that should such an intrusion occur, the dike dimensions are expected to be1 to2 meters wide by 0.5 to 1 kilometer in length. In Sketch 1-1, two dikes (which could as easily be one) run the length of the potential repository. A single cinder cone is indicated in the figure, with the approximate dimensions of the Lathrop Wells cinder cone. The Lathrop Wells cone is thought to be polycyclic (Wells et al., 1990), erupting most recently about 25,000 years ago, so the entire volume of the cone may not be produced as a single event. This becomes important when mechanical details of the eruptions are developed.

When it is energetically advantageous, an advancing intrusion will extend laterally forming a sill (a horizontal tabular intrusion). Since the integrity of the potential repository horizon is reduced by the tunneling and associated fracturing, it is likely that there will be flow from the dikes into void spaces above the backfilled potential repository drifts, as shown in Sketch 1-2. Since it is likely, such a sill is included in the scenario descriptions under Intrusion Acts Directly on Repository α_1. It is not clear, however, that a connected tabular sill bridging drifts, as illus-

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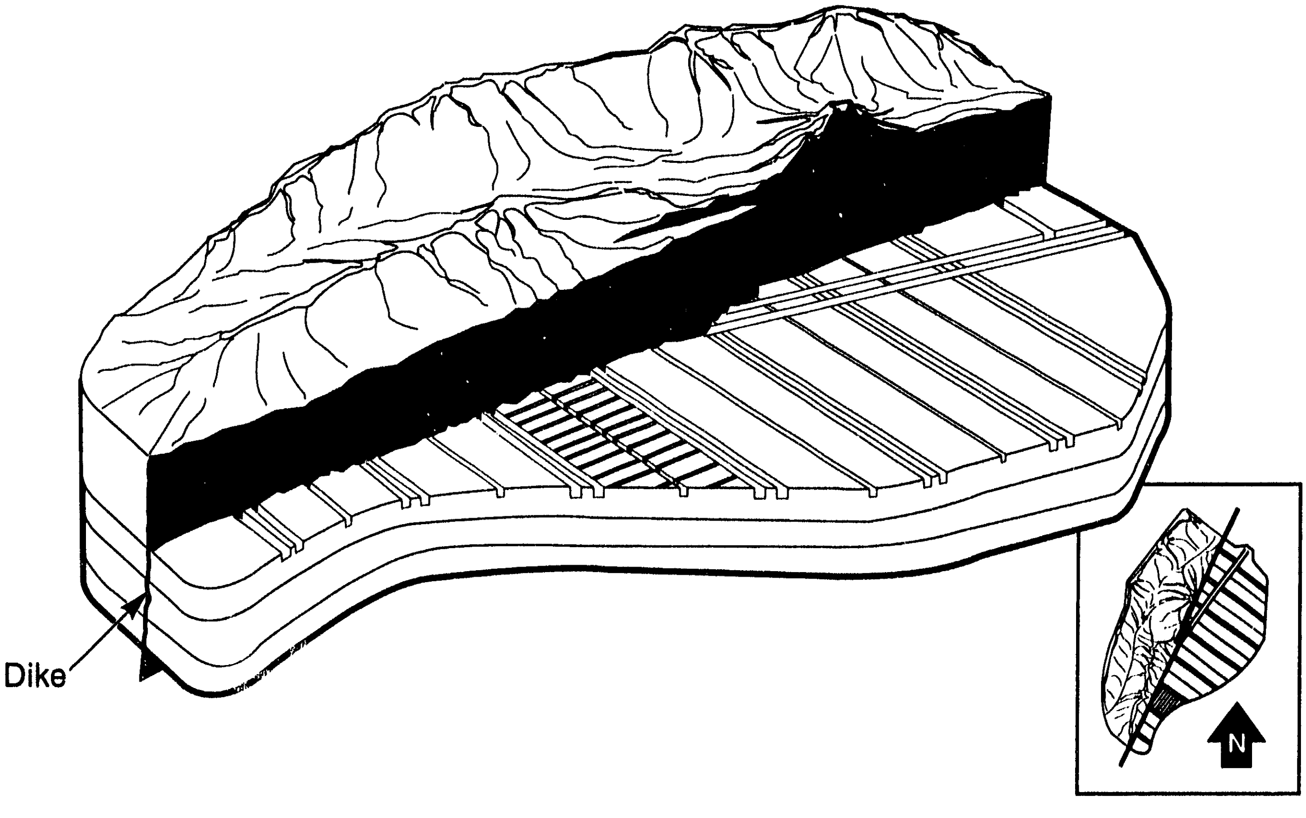
† An intrusion not reaching the surface would produce a branch set that is a subset of the intrusion that does reach the surface.

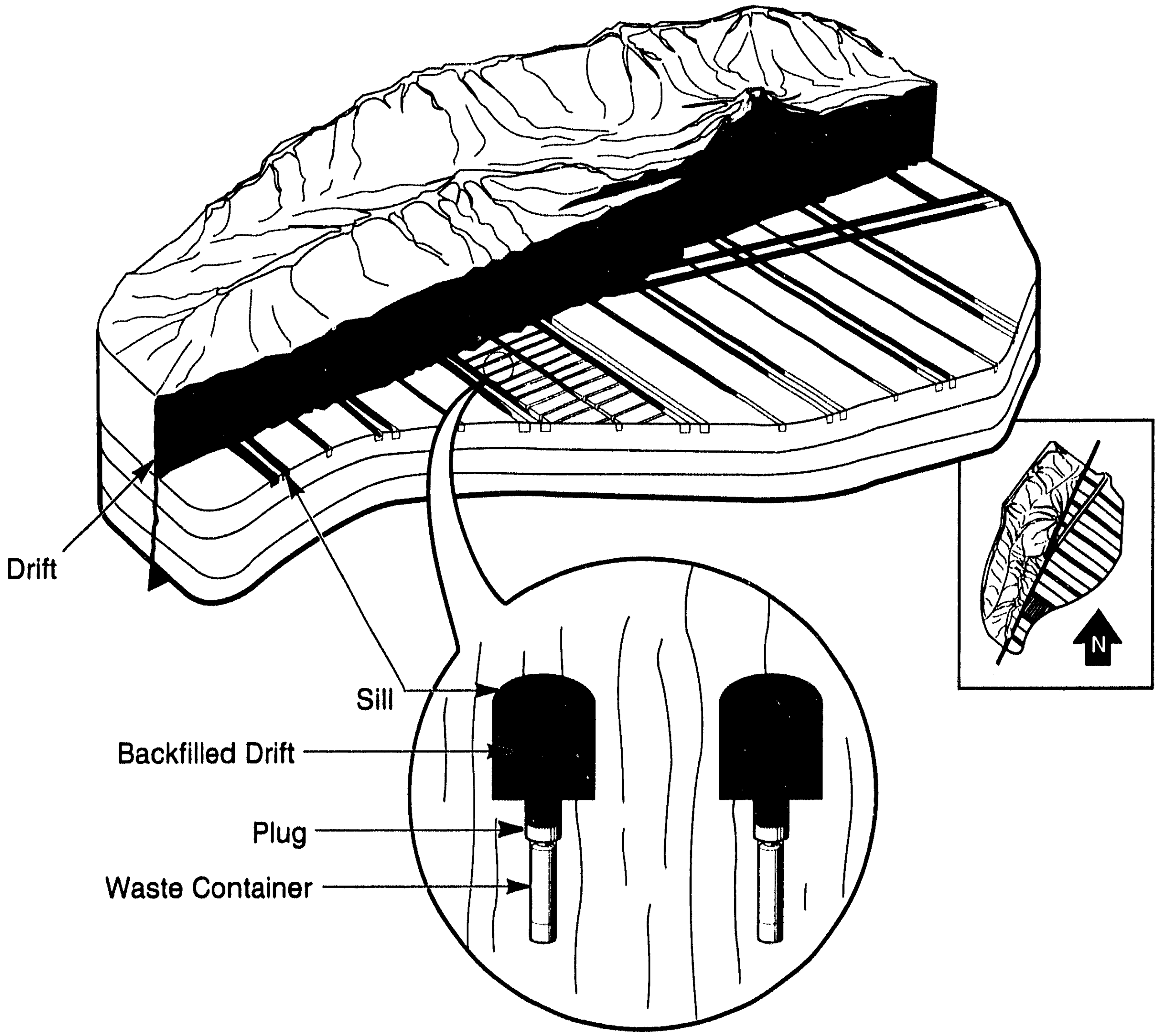
trated in Sketch 1-3, will occur. This problem will be addressed in the discussion of Formation of Sills γ_5.

Using the schematics (Sketches and descriptions) of the paradigms for Intrusion Acts Directly on Repository α_1 with the event tree, one is able to recognize a number of paths through the tree having sufficient detail included to construct well-posed problems: that is, by the definition of scenario used here, a number of distinct scenarios. Some of these scenarios will always occur together, even though they describe different processes; some may occur separately. In the remainder of the chapter Basic Scenarios, we will describe the collection from the given paradigms as completely as possible and add to the description any other recognized scenarios not included in the representative setting.

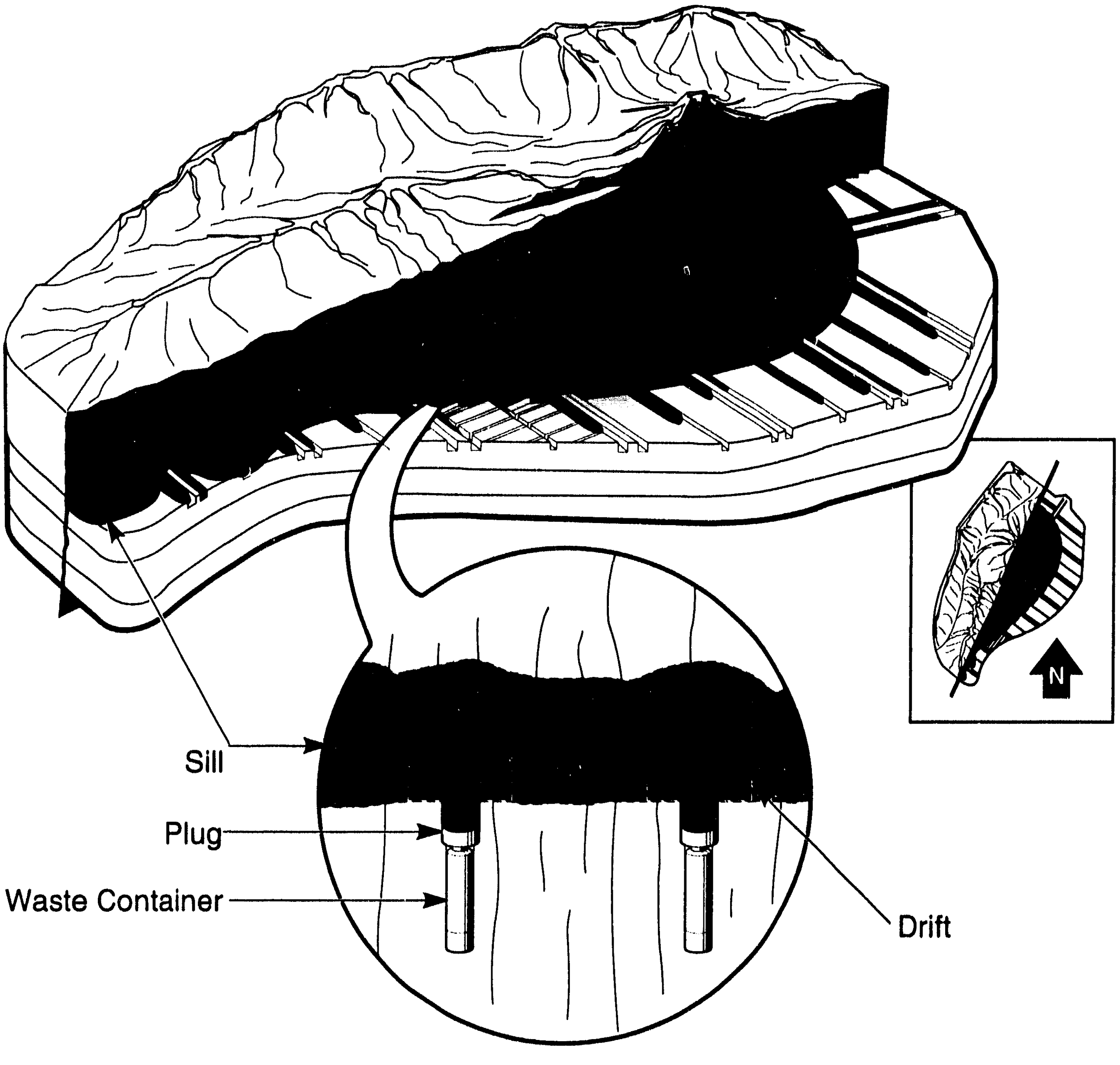
Sketch 1-1 schematically initiates the description of events and processes occurring in the branch of the tree labeled Intrusion Acts Directly on Repository α_1, which continues to Dike Forms β_1. Using the tree as a guide, we construct and discuss scenarios for this branch. Sketch 1-1 shows two dikes intersecting the potential repository; for the case Transport of Waste Intact γ_1, they are presumed to intersect emplaced waste containers.



Sketch 1-1. Dikes intersect potential repository.



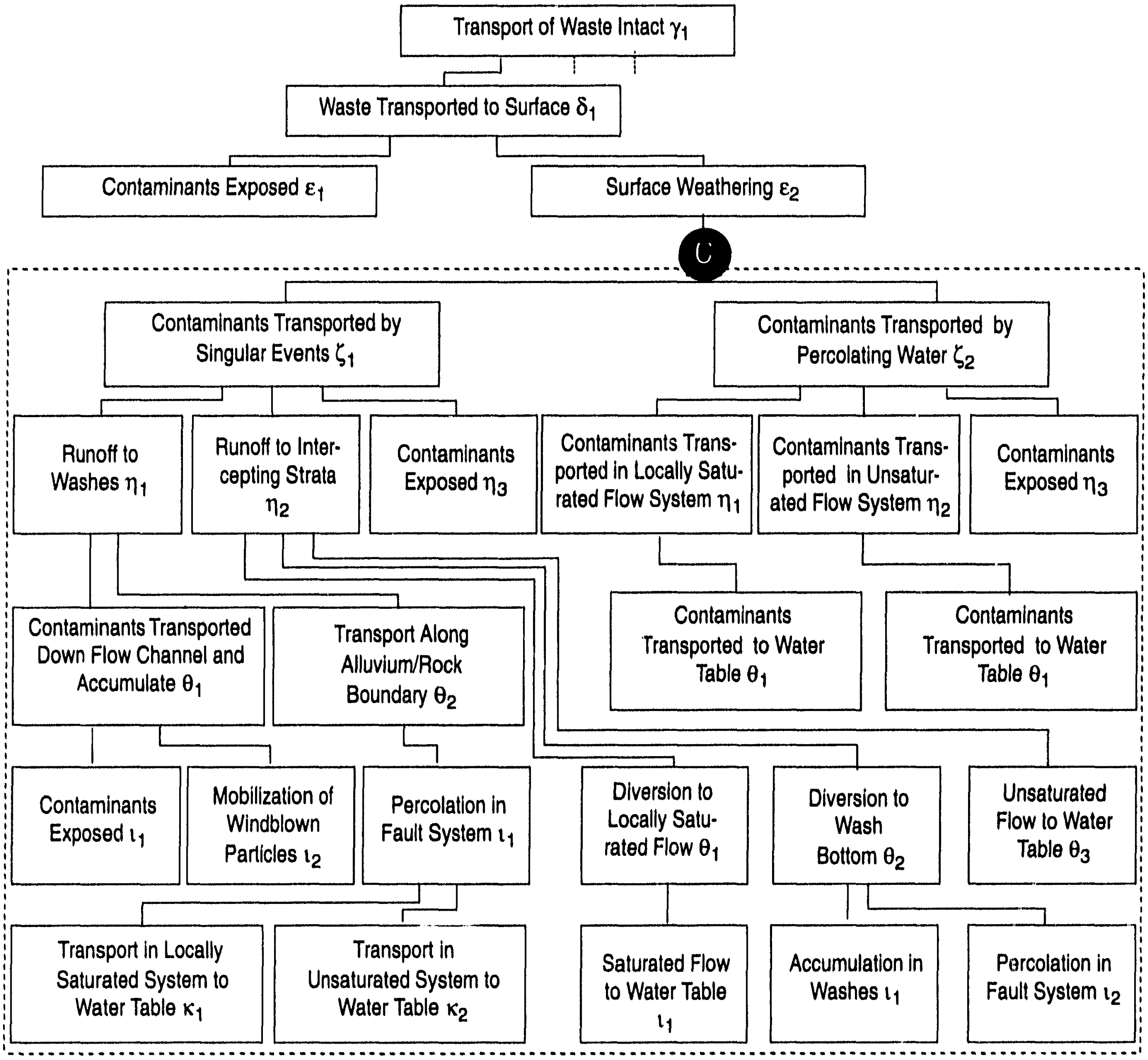
Sketch 1-2. Dikes intersect potential repository producing drift filling sills at the potential repository horizon.



Sketch 1-3. Dikes intercept potential repository horizon and produce a sill that bridges drifts.

Transport of Waste Intact ($\alpha_1, \beta_1, \gamma_1$)

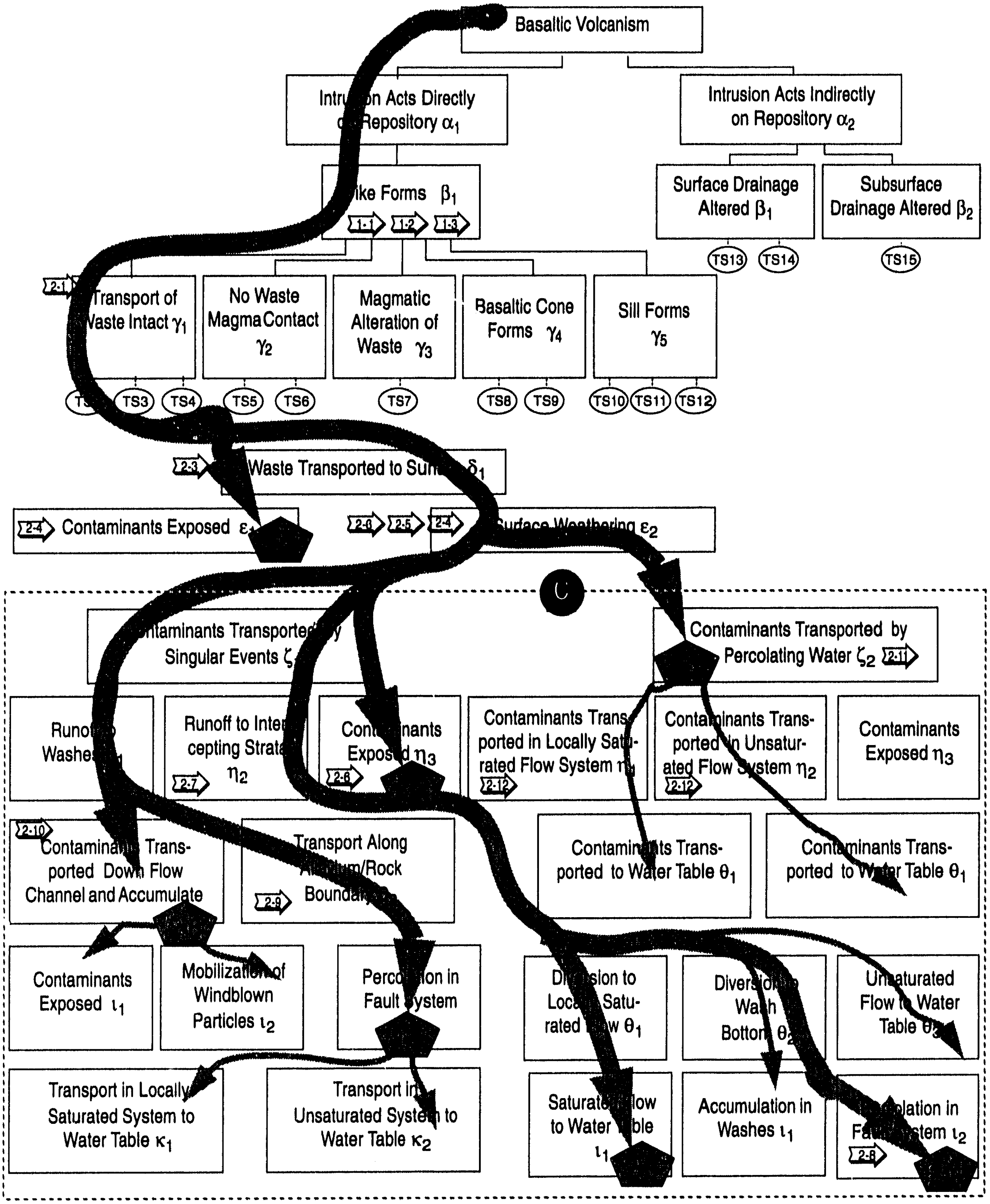
Transport of Waste Intact (α_1, β_1, γ_1) is the leftmost branch of Dike Forms β_1 in the Event Tree.



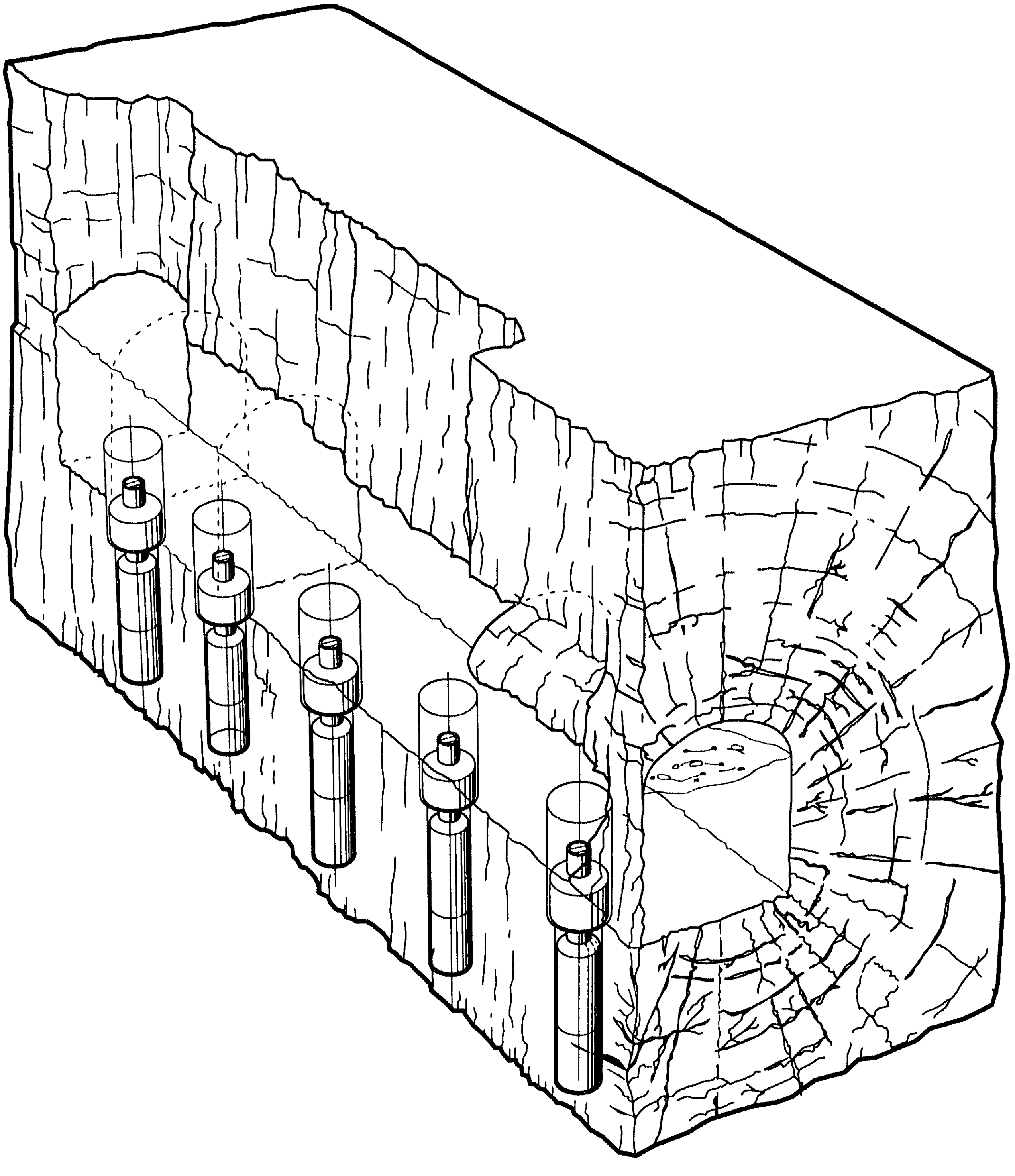
Tree Segment 2a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, transport of waste intact γ_1, waste transported to surface δ_1.

Waste Transported to Surface (TS2) .

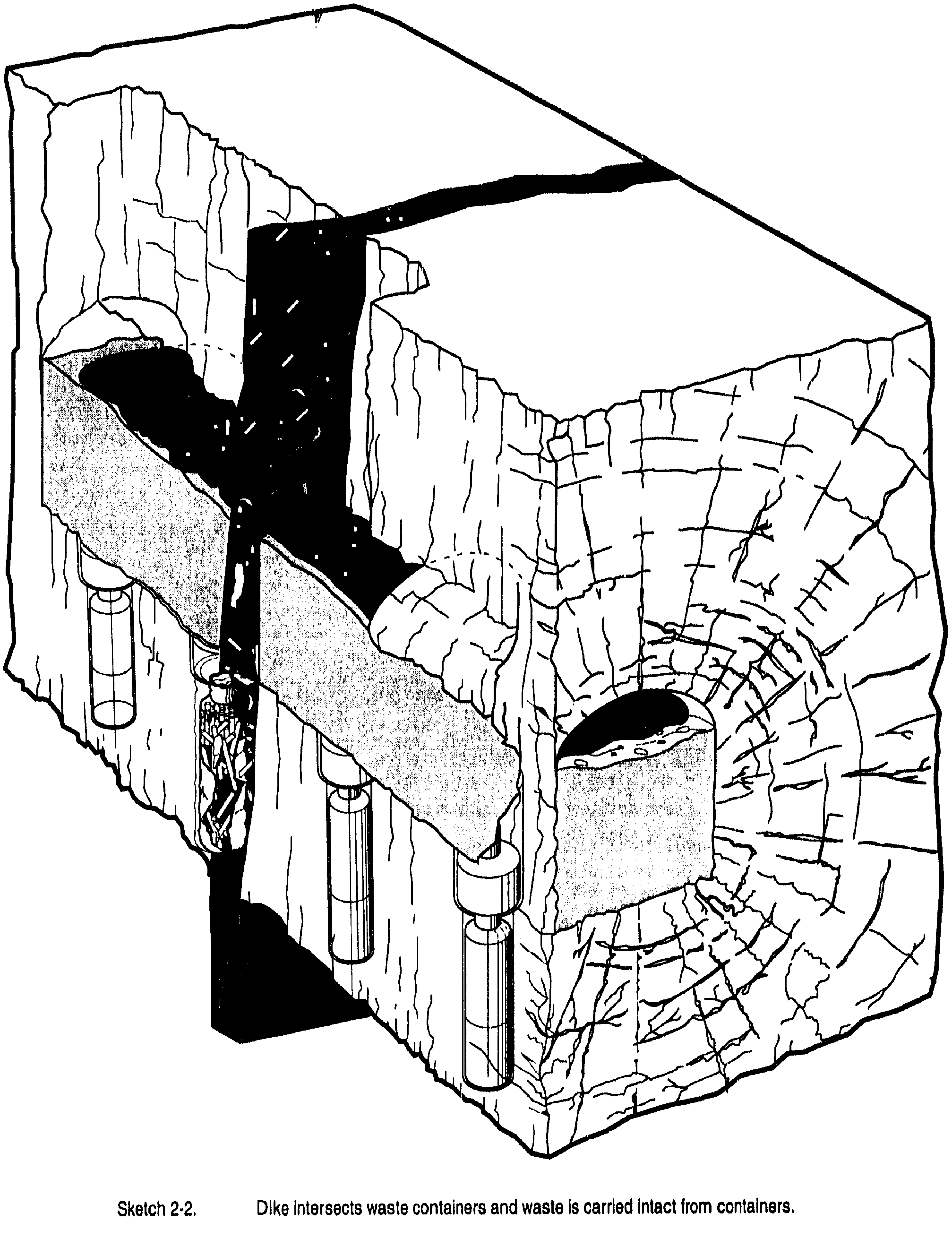
We first construct the scenarios involving intersection of the dike and containers resulting in Waste Transported to Surface δ_1. Sketch 2-1 points to the condition of the rock due to driving the drift; that is, the creation of a stress-altered region around the drift that may influence how a dike and attendant sill flow past the potential repository to the surface. Sketch 2-2 illustrates interaction of the intrusive and container contents. The flowing magma plucks up spent fuel



Tree Segment 2b. Scenario paths and scenario group paths of tree segment 2a.



Sketch 2-1. Illustration of possible fractured condition of rock due to the driving of a drift.



Sketch 2-2. Dike intersects waste containers and waste is carried intact from containers.

rods or fragments from the container and carries them up along with it. This sketch includes flow of the intrusives through the voids down the backfilled drifts.

For Tree Segment 2b we have no alteration of properties of the spent fuel fragments. Spent fuel is refractory relative to the temperature of magma, which is approximately1100 °C, so the presumption that the spent fuel is mechanically incorporated into the magma flow is reasonable. Glassified waste, an alternative waste form, is not refractory and will be considered later, in the section Magmatic Alteration of Waste γ_3, which includes processes of alteration and reaction. The conditions of the containers and the spent fuel at the time of intrusion are more problematic.

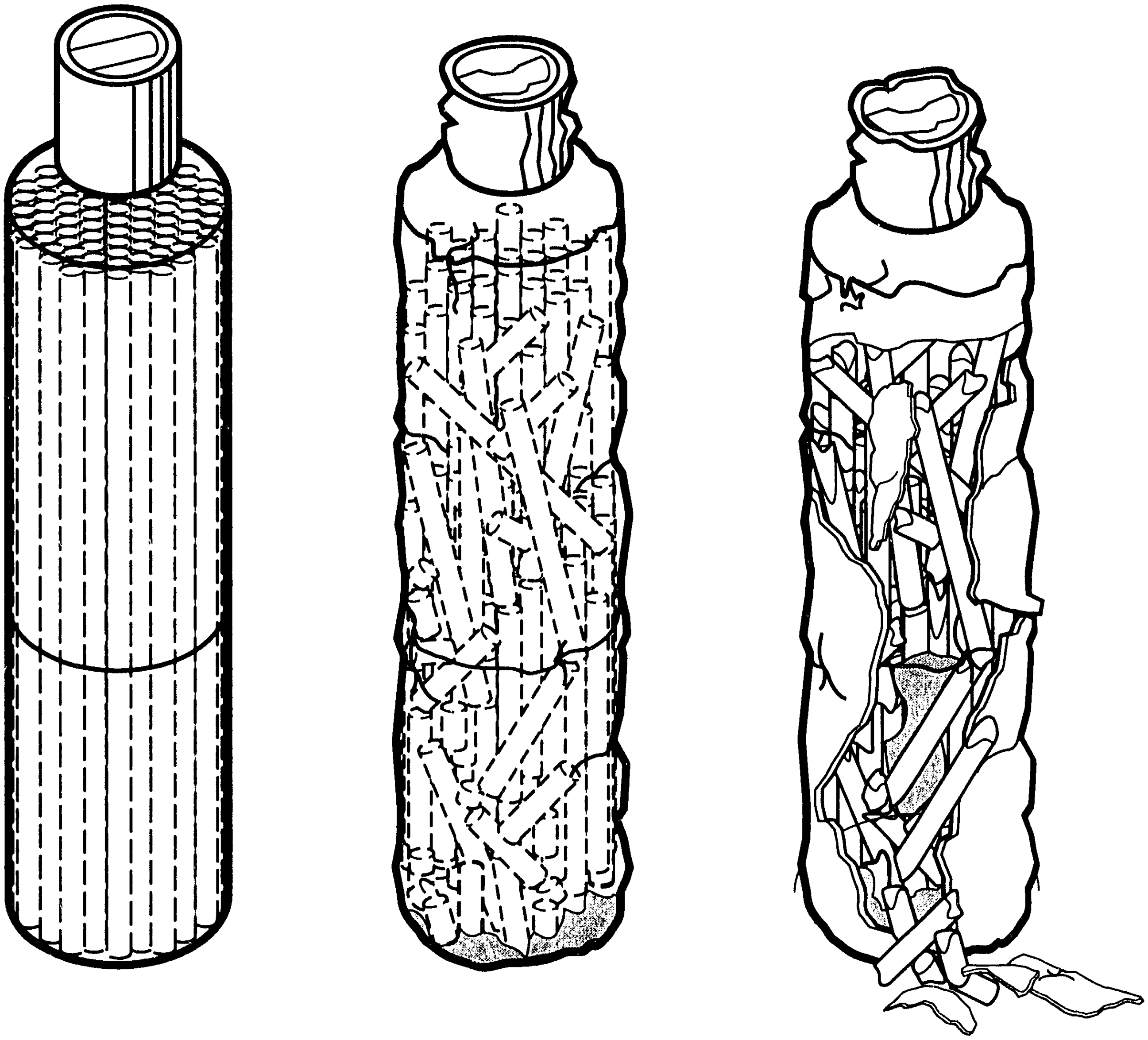
Sketch 2-3 illustrates possible conditions of container and fuel rods. The spent fuel spilled from damaged rods should be expected to vary from mostly-intact pellets to lumpy sand. Transport of intact waste requires a detailed understanding of the mechanical movement of the solid pieces by the magma. Whether such material can be transported to the surface or how it is distributed along the dike is a matter for calculation and analysis.

Considering transport to the surface by the dike, the idea of contaminants exposed is in Sketch 2-4, namely, that biological exposure requires physical contact with the dike and associated ejecta containing the distributed contaminants. Path 2-1 through the tree, as just described, constitutes a scenario for direct release.

In addition to scenario 2-1, there is a series of scenarios branching from Waste Transported to Surface δ_1, involving specifics of Surface Weathering ε_2 and transport of contaminants along the surface or into the ground. These scenarios differ by the form of infiltration, which is preserved in these discussions because descriptive mathematical models are likely to differ. Each scenario in this group includes the sketches indicated in paths shown in Tree Segment 2b.

In Sketch 2-4, it is presumed that the pieces of spent fuel are distributed in the dike and in the ejecta apron associated with the dike. Dike and apron are blocking a wash that formerly drained the slope. Precipitation falling on the mountain and the dike can infiltrate the area of incidence or can run off. That portion participating in evapotranspiration (ET) is presumed to make no contribution to releases and is thus not included in the discussion. Singular events are taken to be rapid, perhaps heavy precipitation capable of producing surface runoff. Examples would be thunderstorms and rapid snow melt. Such events may produce channel and sheet flow with different effects on contaminant transport. Several paths are developed below Contaminants Transported by Singular Events ζ_1 reflecting these possibilities. Contaminant release path 2-2 includes erosion of the basalt surface and exposure of previously enveloped spent fuel debris, allowing the possibility of direct exposure as in Sketch 2-6; or erosion of the fuel particles which then are transported overland and deposited in the accumulation zone of the flow channel, as shown in Sketch 2-10, again allowing the potential for direct exposure.

In the case the dike blocks a wash, one expects blockage to be eventually downcut, perhaps to a narrow channel as in Sketch 2-5. Even without such a channel, runoff can carry debris particles and contaminants mobilized from the sides of the apron and from gullies eroded into the apron (as in Sketch 2-6) down-slope to enter the hydrologic flow system of the wash. One suggested entry is into exposed fractured strata on the wash side-slopes, as in Sketch 2-7. 2-3 continues with the intercepting fracture system feeding a locally saturated flow system that extends to the water table, and 2-4 continues with the intercepted flow being diverted to the wash edge and bottom through fractures. Some of the washes, particularly at the north-

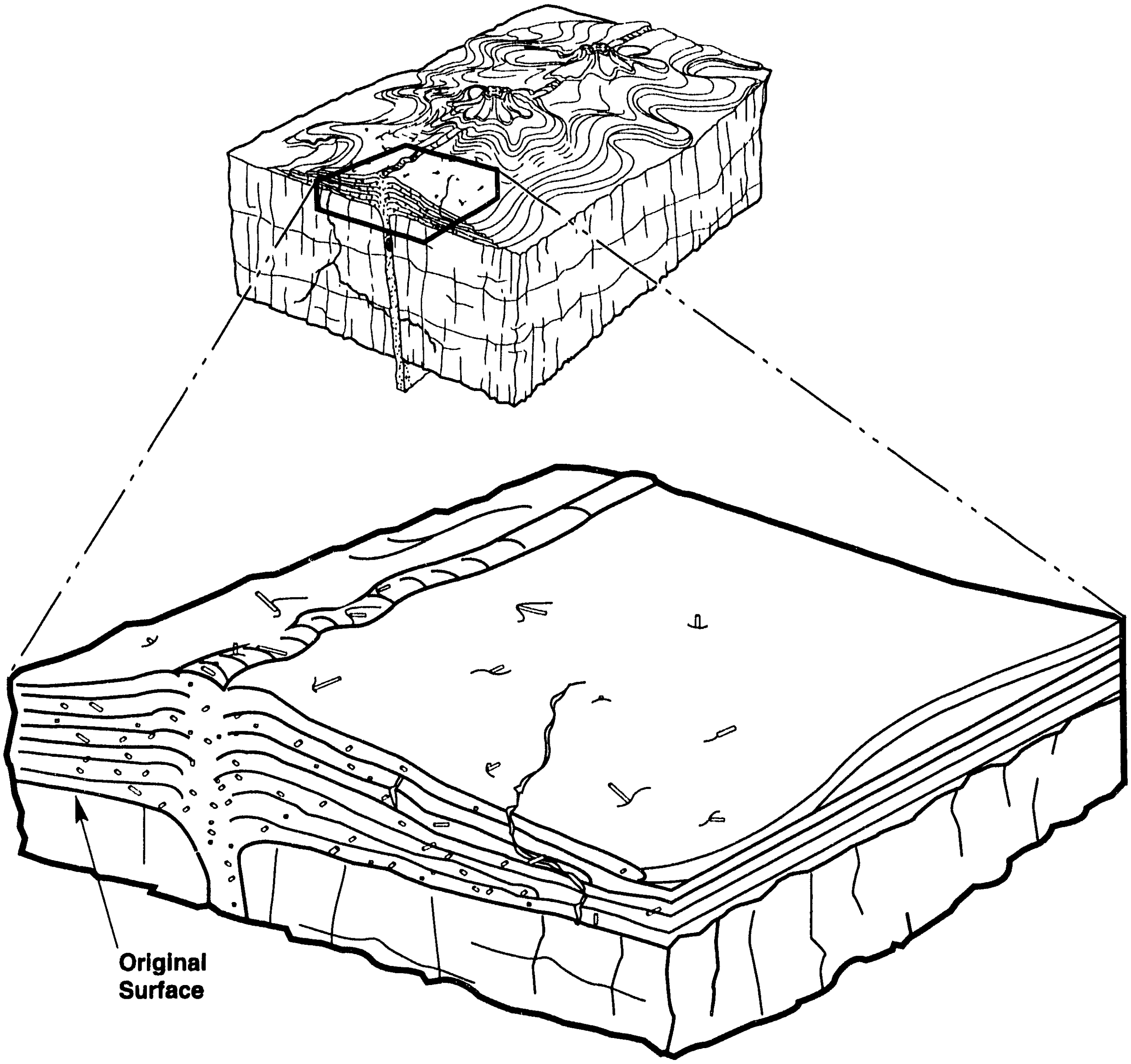


Pristine

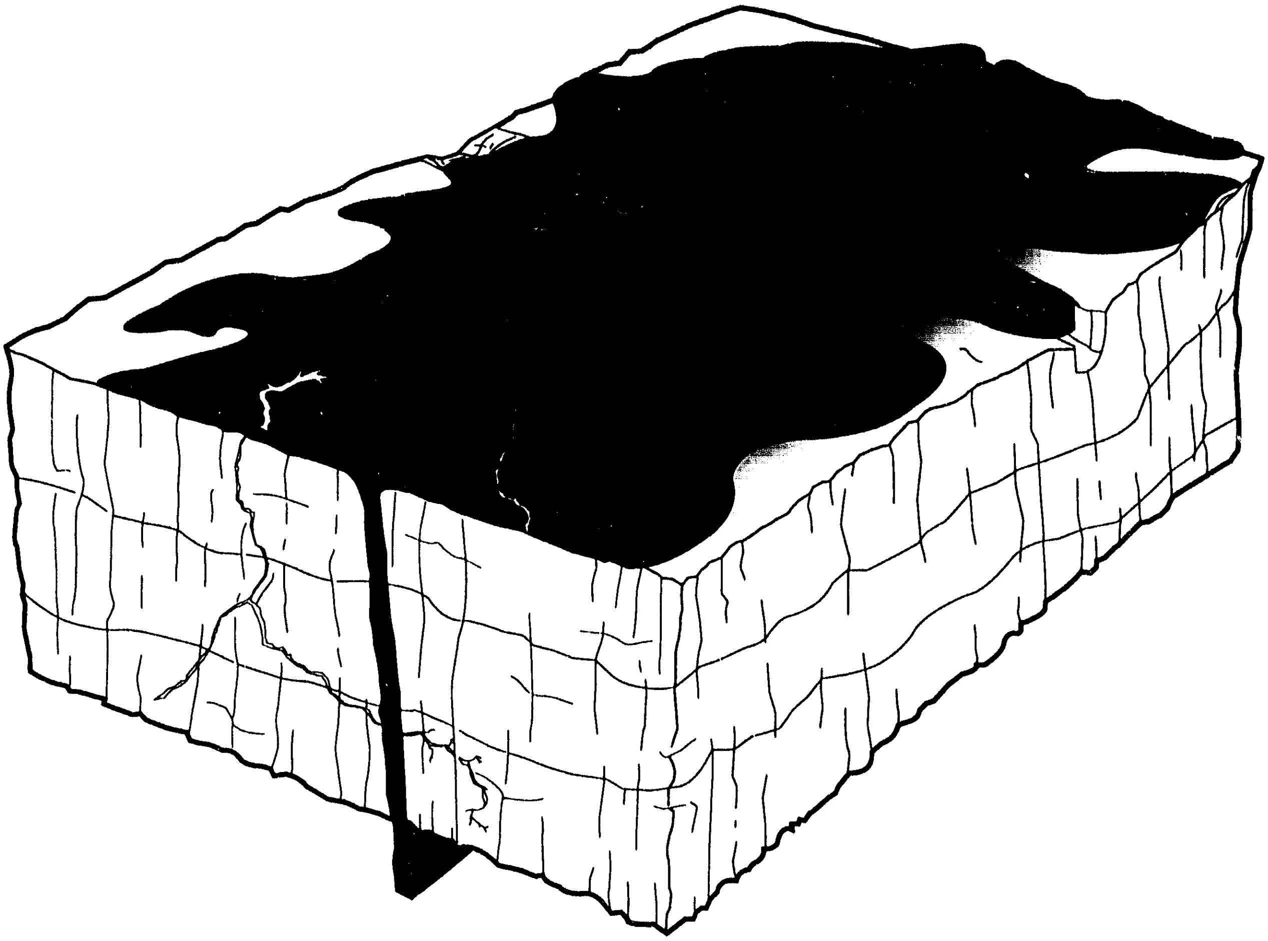
Microseismic Damage

Corrosion and Seismic Damage

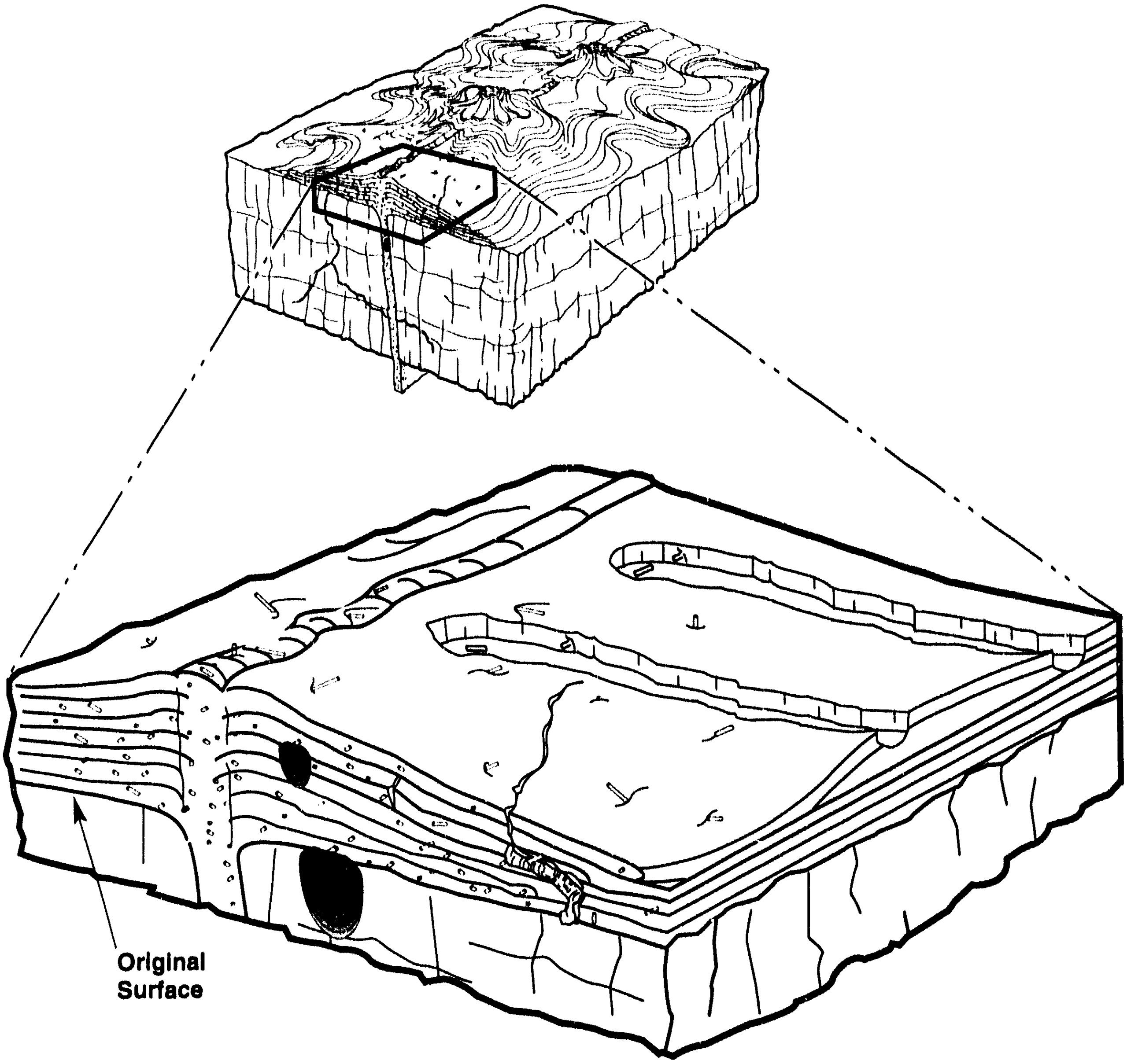
Sketch 2-3. Possible conditions of waste containers include pristine, damaged by microseisms, and corroded.



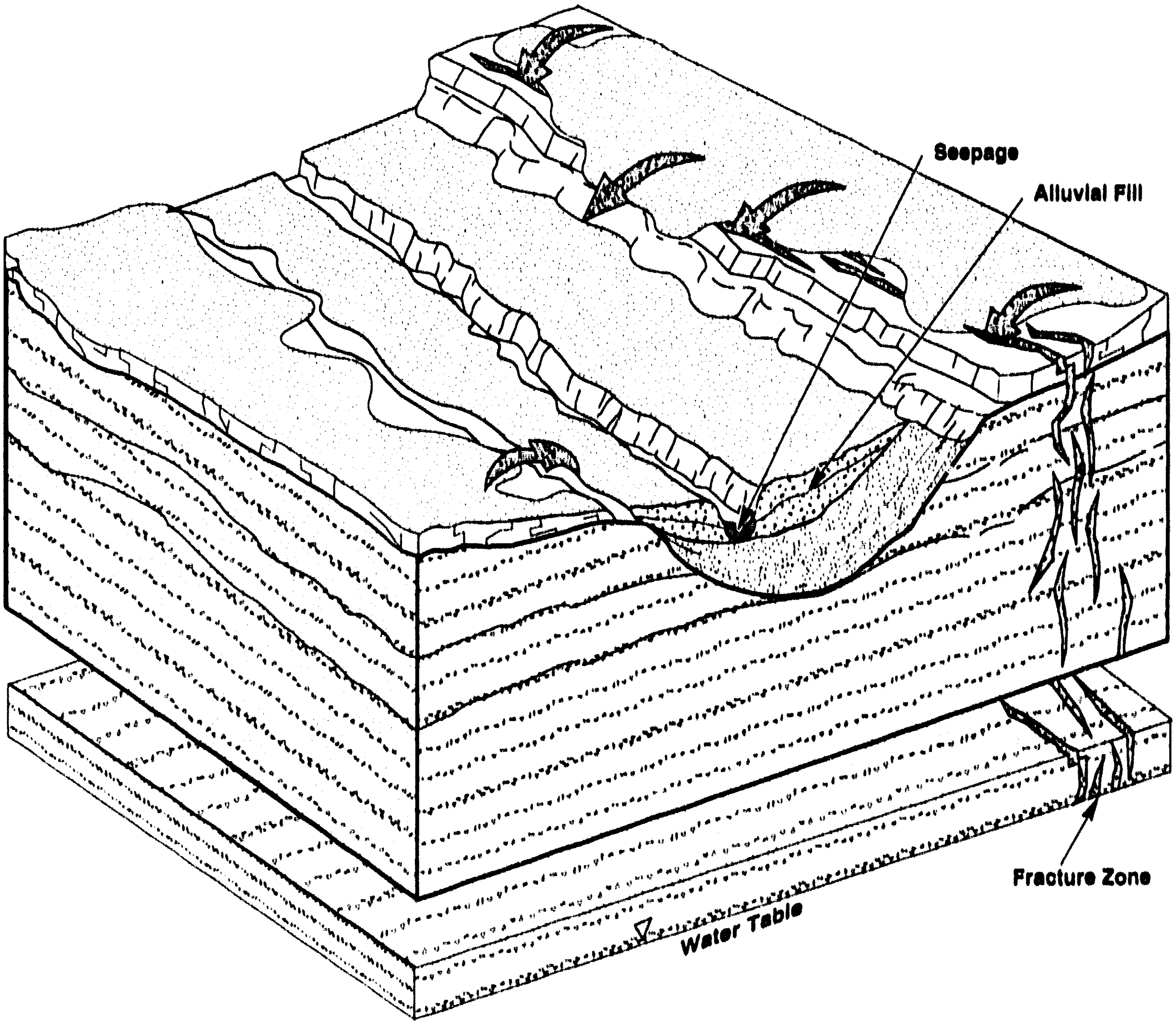
Sketch 2-4. Dike carries waste to the surface, allowing contaminants to be exposed.



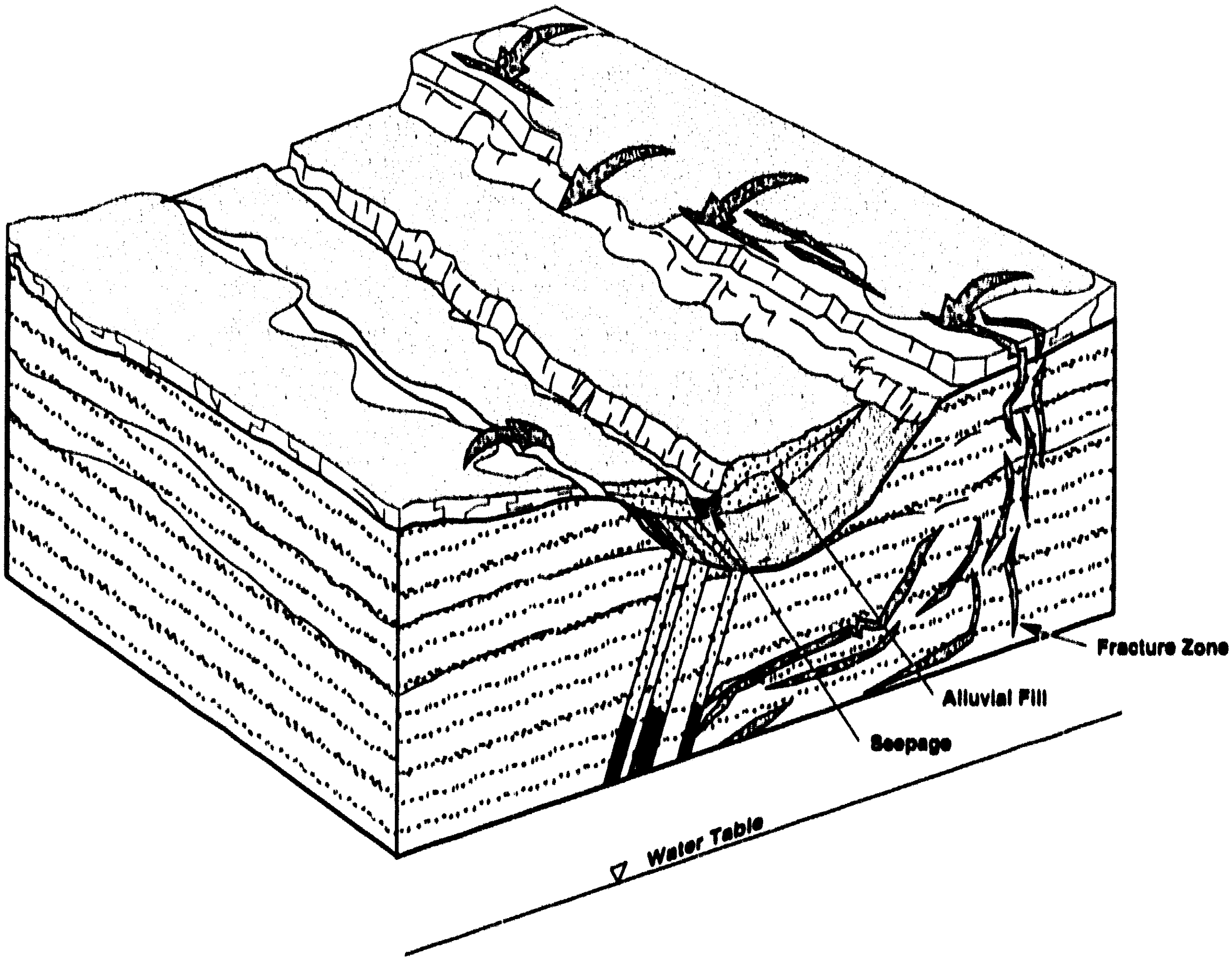
Sketch 2-5. Steep-sided channel is cut through a dike blocking an old wash channel.



Sketch 2-6. Gully erosion of ejecta apron unearths contaminants, thus permitting direct exposure.



Sketch 2-7. Contaminated water flows down side-slopes and enters fracture zone extending to the water table.



Sketch 2-8. Contaminated surface flow enters fractured strata and finds fracture pathways to faults beneath washes.

ern end of the block, are apparently fault-controlled. Sketch 2-8 shows the continuation of these paths to Percolation in Fault System ι_2. Faults could provide a path to the water table without requiring an inordinately long residence time for transport. This Sketch shows the fluid movement down faults with differences between unwelded and fractured-welded units simply indicated schematically by including local perching along the fault. Faults that are conduits as well as partial barriers are conceivable.

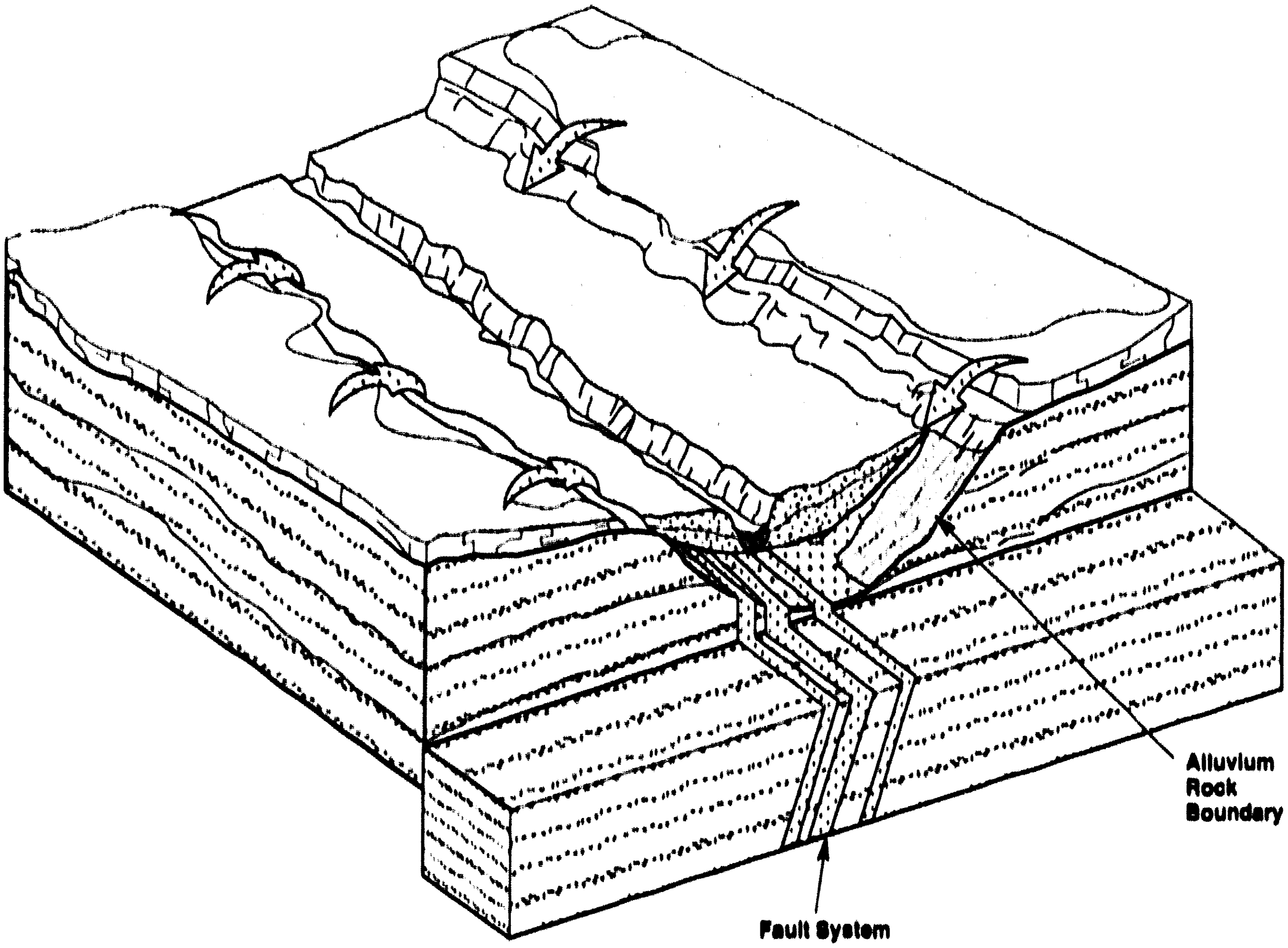
Some of the flow will be captured in fractures of intercepting strata and enter the unsaturated flow system in the mountain. Presumably this would imply a long residence time for travel through to the water table. While this is a conceivable scenario, we will not complete the expansion here, for the reason that the path is greater than that of any contaminants in the potential repository. If field studies show short circuits are possible, this scenario will be added to the tree and will be reexamined.

Returning to Contaminants Transported by Singular Events ζ_1, and now consulting 2-5, and 2-6 and associated Sketches, we see the possibilities described as the FEPs Contaminants Transported by Singular Events ζ_1, Runoff to Washes η_1, Contaminants Transported Down Flow Channel and Accumulate θ_1, and Transport Along Alluvium/Rock Boundary θ_2, where the branching describing the fate of contaminants in weathering is chosen to be consistent with the current understanding of surface infiltration (DOE, 1990).

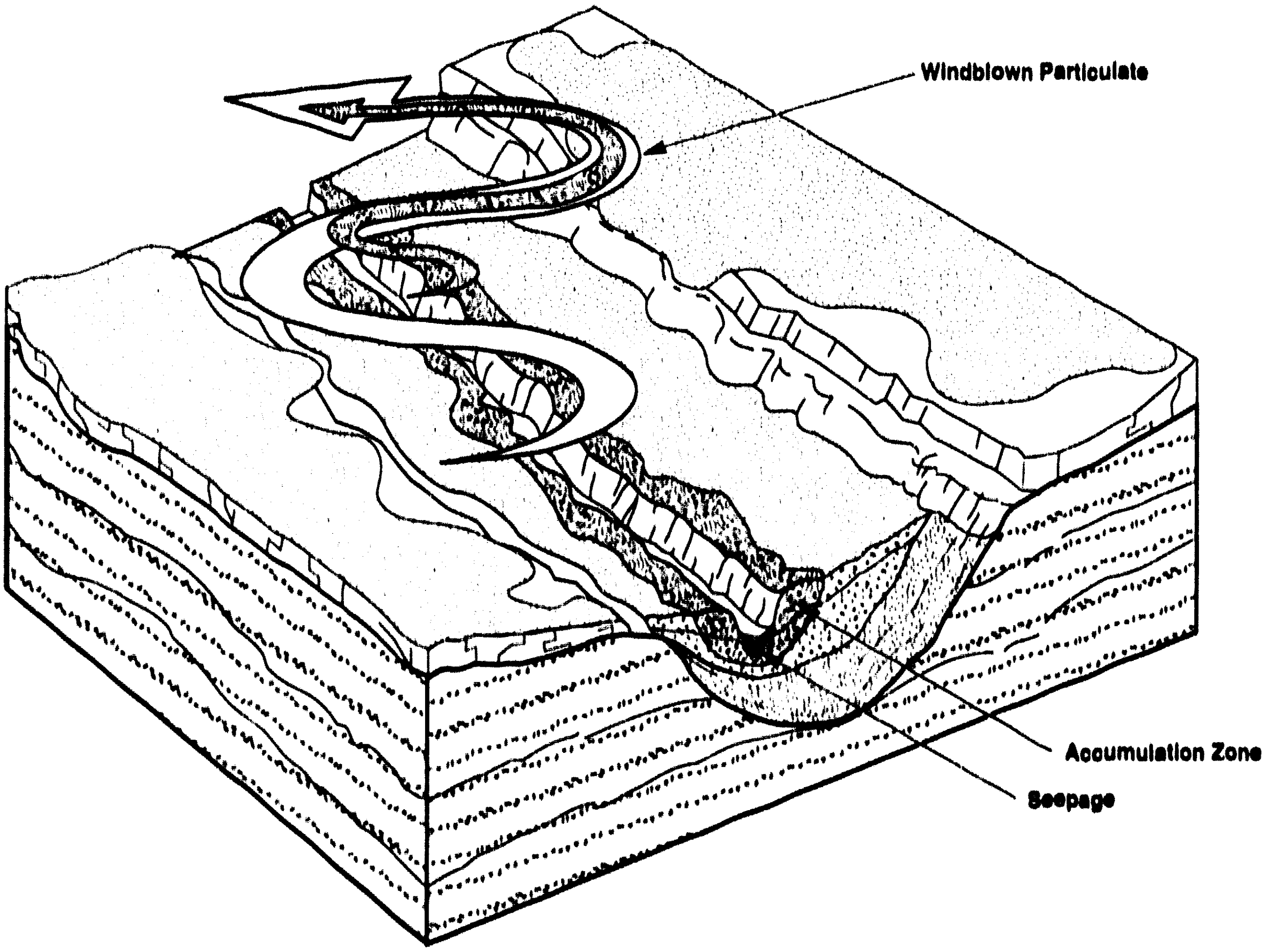
Presumably the flow channel is the major conduit for runoff, especially for runoff during singular events such as thunderstorms. Sketch 2-9 illustrates the branch of the tree 2-5 with Runoff to Washes η_1 first being directed along the interface between alluvium and rock beneath the washes (Transport Along Alluvium/Rock Boundary θ_2), and then running down a fault system (Percolation in Fault System ι_1) to the water table or to the unsaturated flow system leading to the water table. Clay lenses and caliche layers are other features common under channels that cause lateral flow, and should eventually be included in the modeling of this region. We do not distinguish here between transport in the unsaturated system and transport in the locally saturated system because, even though they have different flow times, the contribution to each is most likely decided by a single computational model. It is also possible for contaminants to accumulate in washes (Contaminants Transported Down Flow Channel and Accumulate θ_1), as in Sketch 2-10, providing direct exposure (Contaminants Exposed ι_1), or upon drying, providing windblown particulates (Mobilization of Windblown Particles ι_2).

As often occurs in arid areas, the stream could end in a dendritic pattern. Options for distribution of this flow include arrest by evapotranspiration or subsurface continuation of flow. Subsurface flow could eventually resurface, and the fluid then evaporate, forming a playa (Czarnecki, 1990). Exposure in this case is by direct contact or by remobilization of particulates on the dry surface by wind. 2-6 includes these processes.

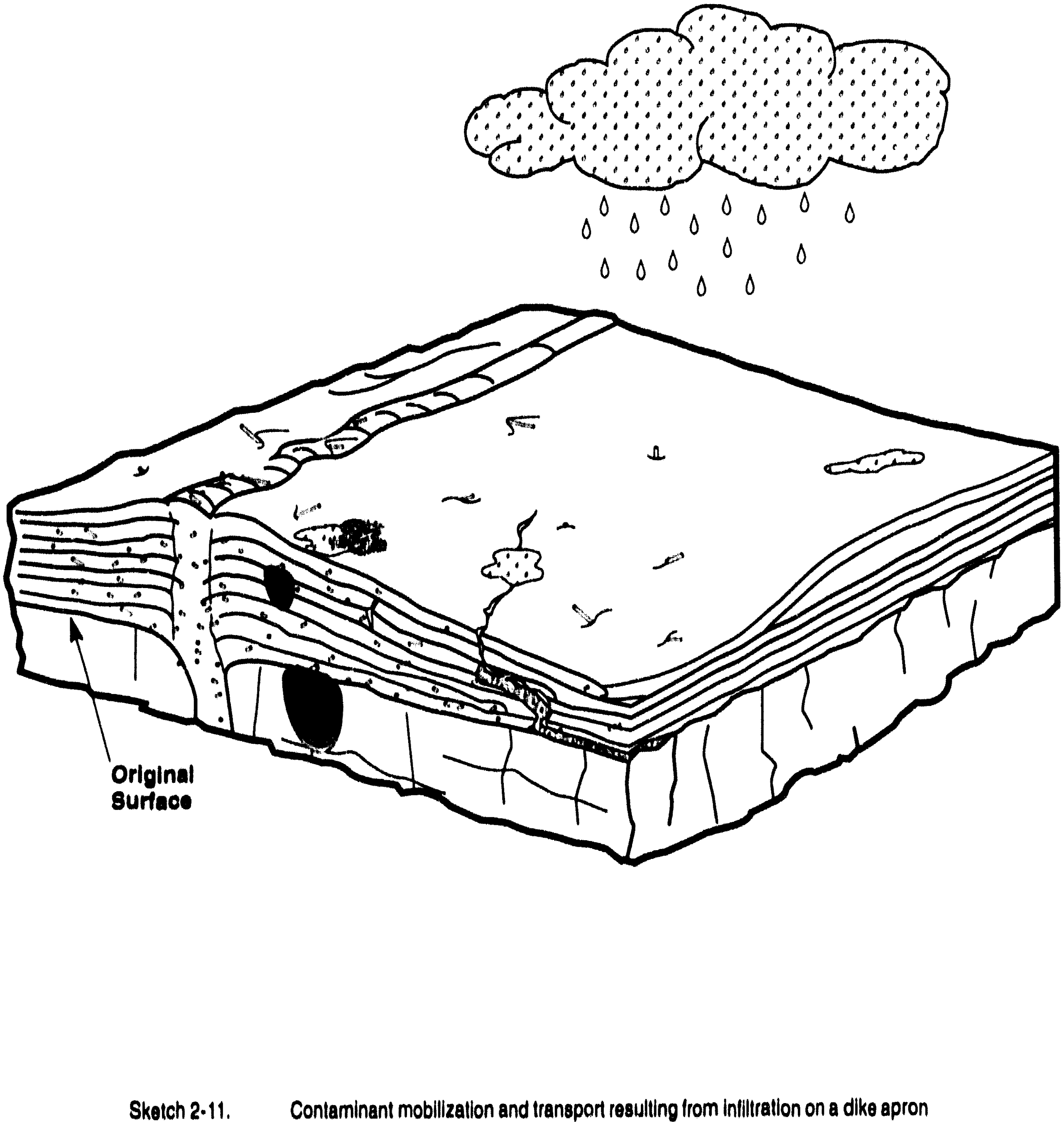
Another possible pathway, Contaminants Transported by Percolating Water ζ_2, is that in which precipitation finds its way directly into and through the extruded and contaminated strata. The ejecta apron will be an aggregated and rough surface supporting inhomogeneous porous materials and fractures. Both pores and fractures act as conduits to carry fluids to or past contaminant pieces. The included spent-fuel debris is weathered in the interaction of water, atmosphere, and rock, allowing leachants to be extracted from the contaminant debris. The immediate fate of such leachates will be expected to depend on the hydraulic properties of the dike. Following 2-7, if the permeability contrast between the preeruptive surface and dike ejecta permits, the leachates move along this interface until exposed at the surface; otherwise, the leachates from the dike and apron enter the unsaturated or the locally saturated flow system associated with nominal flow in the mountain. Sketches 2-11 and 2-



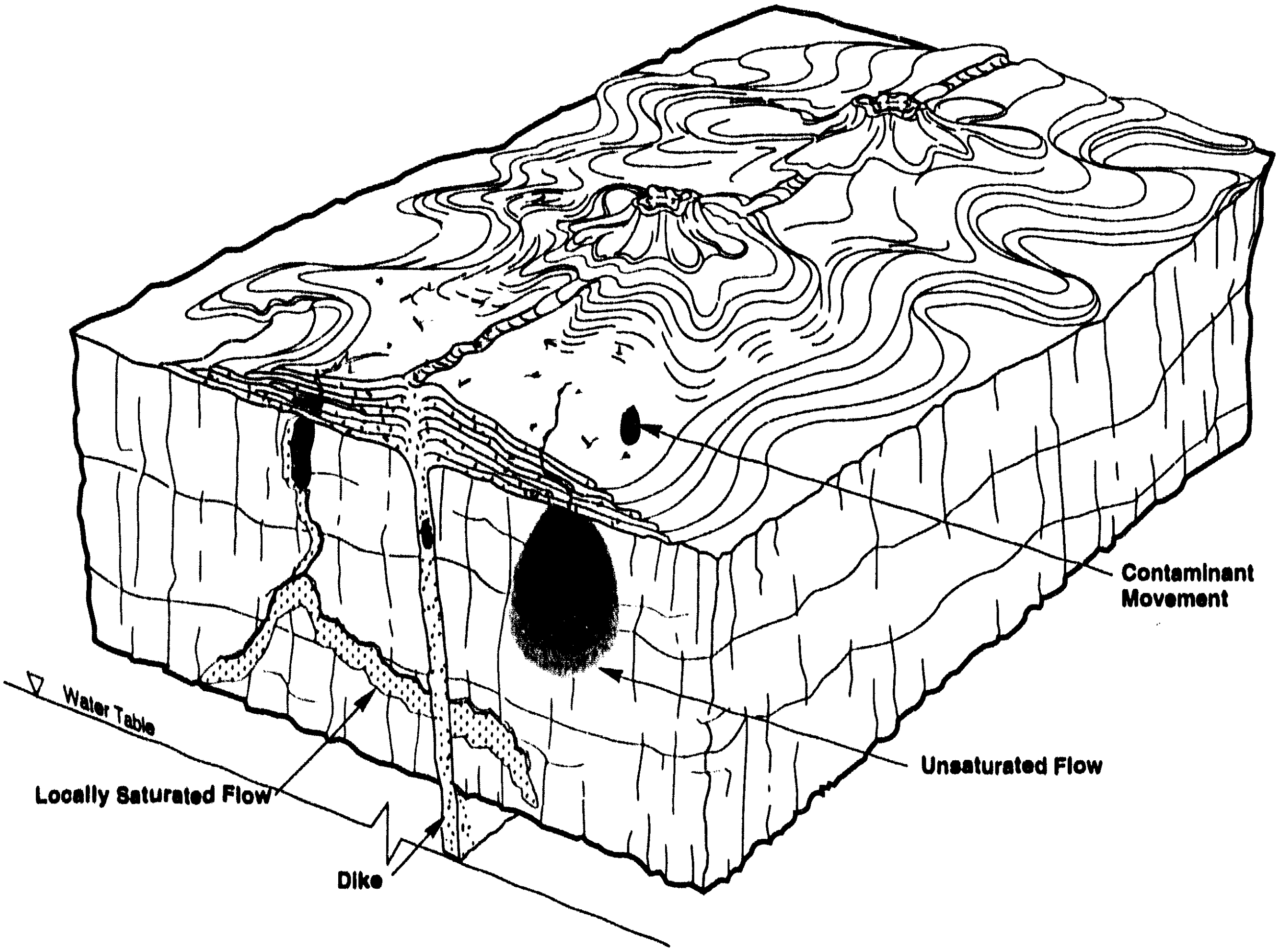
Sketch 2-9. Flow along alluvium/bedrock boundary enters faults.



Sketch 2-10. Stream deposits contaminants along channel. Wind spreads dried contaminants along with sediments.



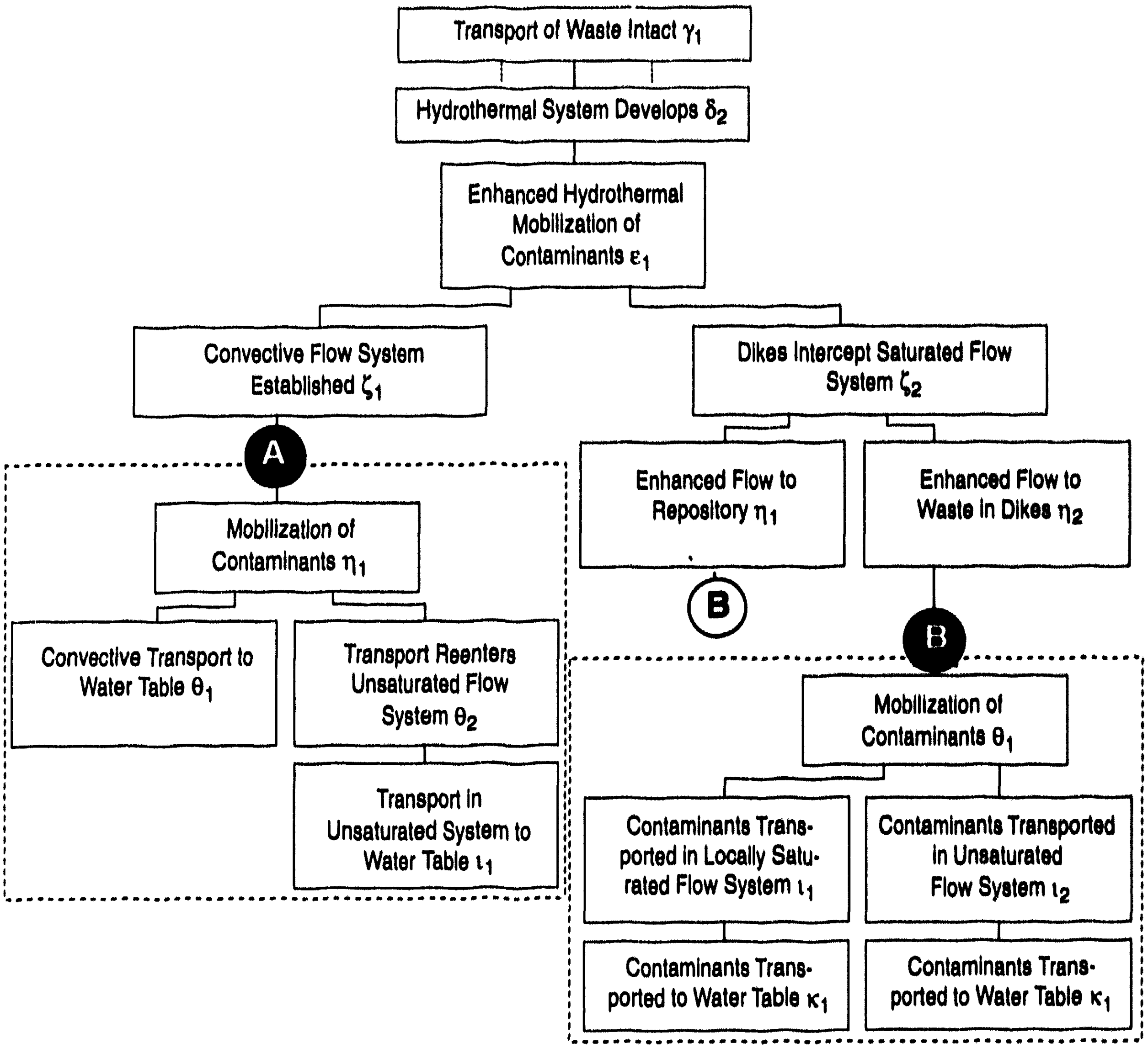
Sketch 2-11. Contaminant mobilization and transport resulting from infiltration on a dike apron containing contaminants distributed by a dike that intercepted a waste container in a repository.



Sketch 2-12. Additional ejecta apron infiltration, mobilization, and transport modes.

12 illustrate movement of contaminants mobilized from fuel element debris into the locally saturated and unsaturated flow systems.

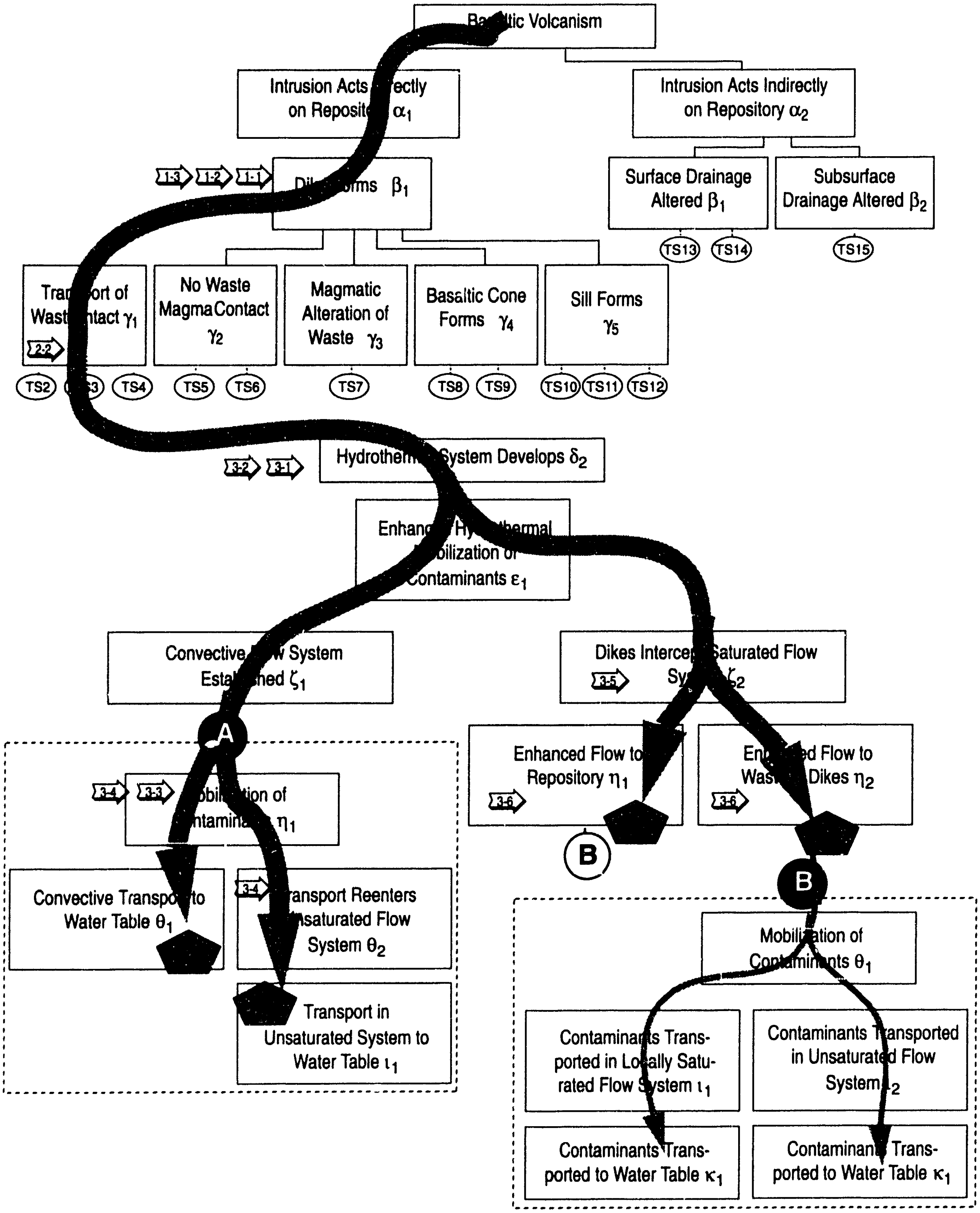
These seven scenarios and groups of scenarios describe transport of unaltered waste to the surface by dikes and subsequent routes to possible human exposure. Additional scenarios for transport of contaminants to the surface occur in the branches Magmatic Alteration of Waste and Basaltic Cone Forms discussed later. The scenarios for these cases will be the same as those just discussed; however, the amount of available waste debris and the geometry of the problem will change.



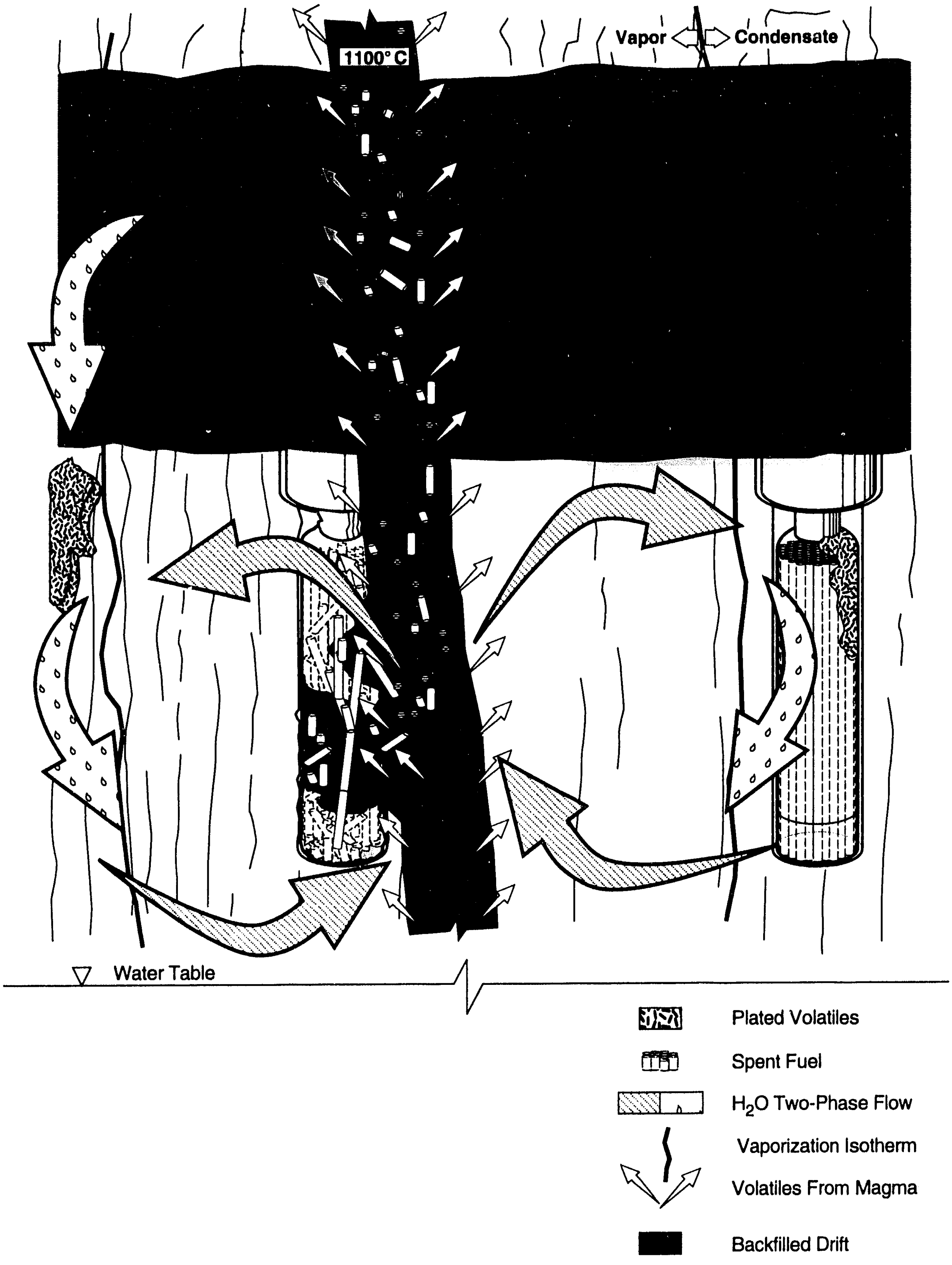
Tree Segment 3a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, transport of waste intact γ_1, hydrothermal system develops δ_2.

Hydrothermal System Develops (TS3)

Intrusion of liquid rock implies that there are also thermal and mechanical alterations to the flow system produced by such an intrusion, even in the absence of magmatic alteration of the waste. First we consider the thermal alterations. The intrusion is approximately 1100 °C during emplacement, and cools primarily by conduction in the unsaturated zone, solidifying over a few weeks and reaching pre-intrusion ambient temperatures in a few tens to hundreds of years, with exact details depending on the thickness of the dike. In the case of Hydrothermal System Develops δ_2, we consider any flow system driven by the heat from the intrusion to be hydrothermal. Since the intrusion intersects both the saturated zone and the unsaturated zone, the effects on both need consideration. One would expect that a two-phase convective flow system would be established close to the dike. Past measurements of dikes



Tree Segment 3b. Scenario paths and scenario group paths of tree segment 3a.



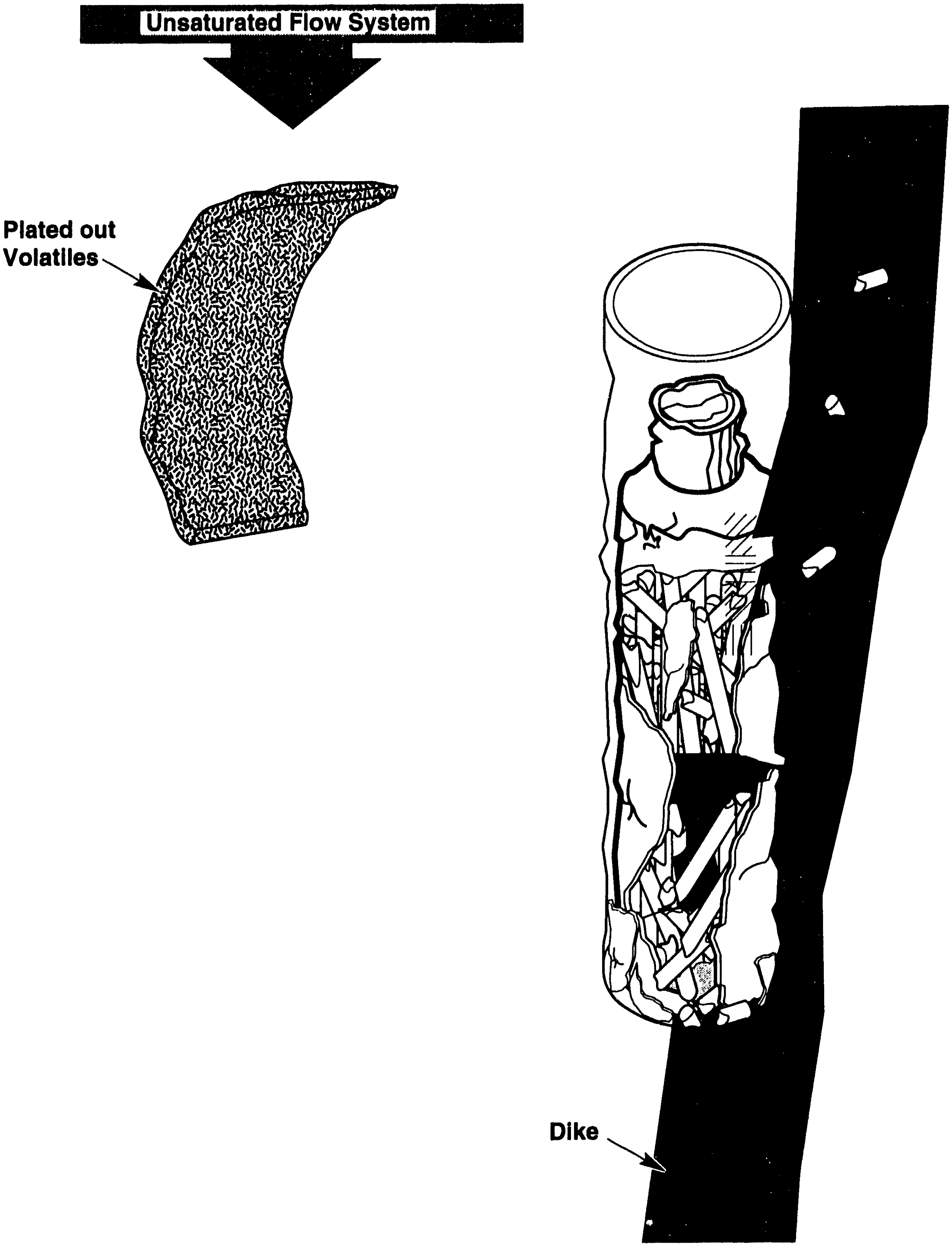
Sketch 3-1. Hydrothermal system develops, driven by the inserted dike of approximately 1100 °C.

(Buchan et al., 1980) and thermal calculations indicate maximum temperatures of several hundred degrees Centigrade on the order of a meter from the typical dike for this region. Sketch 3-1 illustrates the short-term flow dynamics being considered. The intruding dike causes local dryout above the water table and generates two-phase convective flow past the containers. Below the water table there may be local dryout, but it is accompanied by rapid chilling of the dike skin. While the temperature of the dike is above local ambient, the two-phase convection can be expected to persist. Early in the intrusion, local condensation would be expected to occur one or two rows of containers away and parallel to the dike. The enhanced two-phase convection, coupled with the volatiles being released by the intrusion, would be expected to produce aggressive fluids at the waste packages at risk.

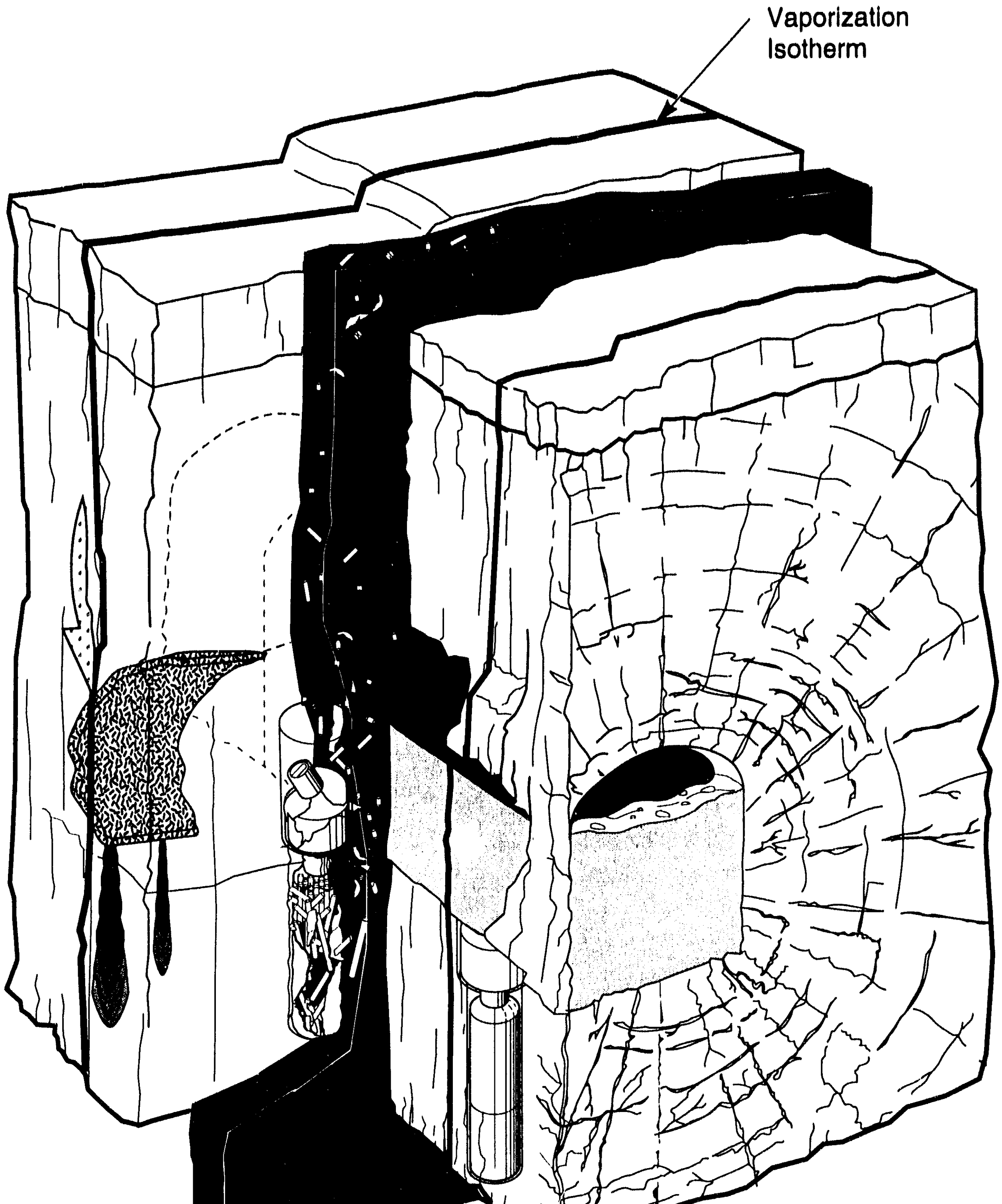
We have come down through the upper FEPs of 3-1 and 3-2 , Hydrothermal System Develops δ_2 and Enhanced Hydrothermal Mobilization of Contaminants ε_1. Since we are concerned with waste that has been transported intact, we only consider the fate of the containers that have been directly contacted.

The next question is how the contaminants are transported. Sketch 3-1 indicates a time-dependent convective flow system may be formed. Because the containers hit by the dike are in the vapor-phase region and fluid movement is up, the volatiles released from the containers condense to the cooler side in surrounding rock, as in Sketch 3-2. Isotherms are roughly parallel to the dike, so condensation occurs at approximately a uniform distance away from the dike. For strata with high enough water content, a locally saturated zone may form along the vaporization isotherm. This zone, if it forms, would follow the isotherm back toward the dike; so, at some time, a locally saturated zone would develop in such strata at the region of volatile plate-out. These contaminants are then the first to be exposed to mobilization from the reflux, saturated or unsaturated, as shown in Sketch 3-3. With further cooling of the dike, the width of that convective system will decrease until saturated reflux passes through the remains of the container. Mobilization of contaminants should continue during the period that the dike can provide the driving mechanism for convective flow without dryout. This scenario continues in 3-1 with Convective Transport to Water Table θ_1.

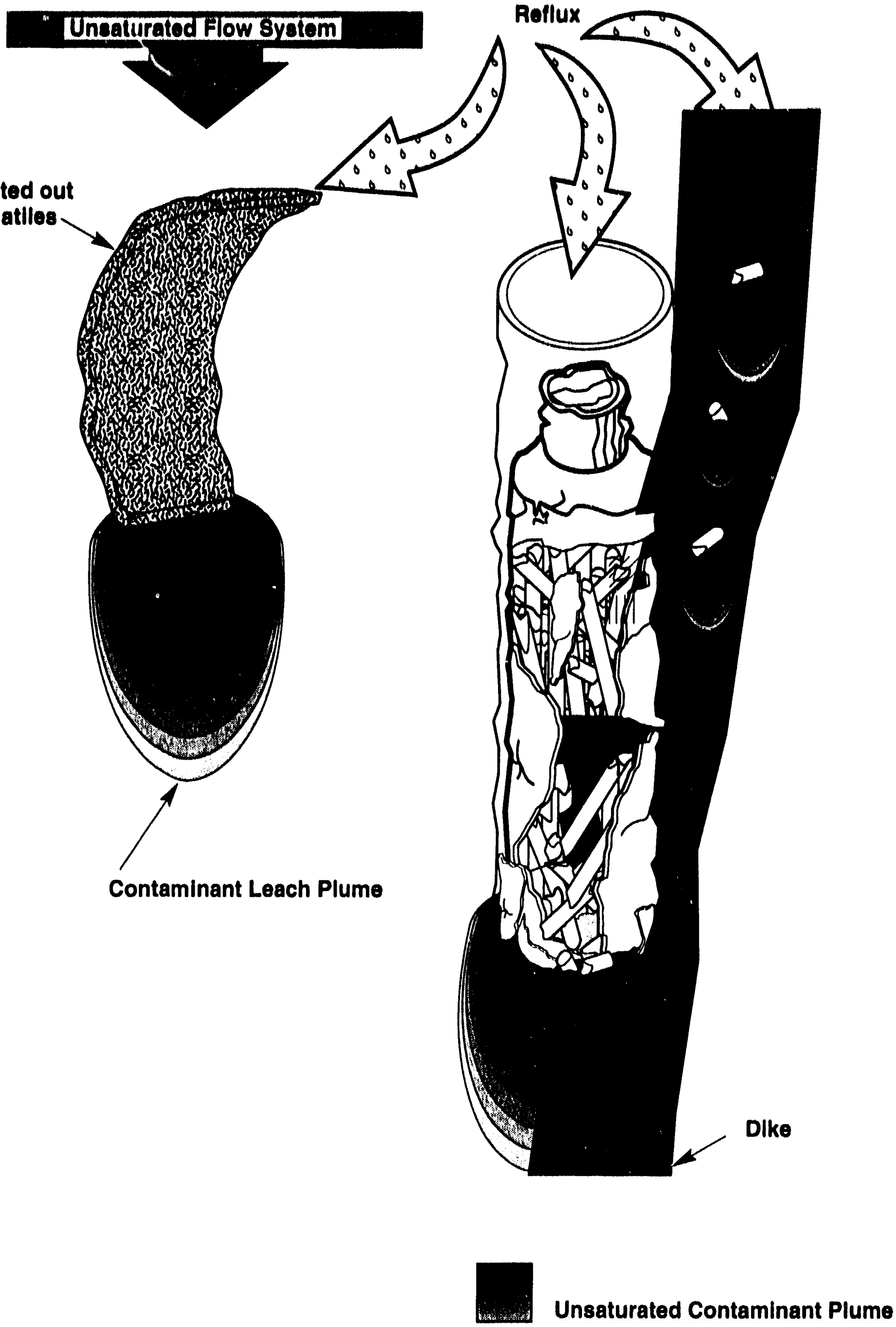
From Tree Segment 3 we realize that there is a possibility of two other pathways for transport after the dike is cool. One, 3-2, is for transport to re-enter the unsaturated flow system (Transport Reenters Unsaturated Flow System θ_2). Several processes for this path are suggested in Sketch 3-4. 3-2 concludes with Transport in Unsaturated System to Water Table ι_1. The other possibility, including both 3-3 and 3-4, is for Dikes Intercept Saturated Flow System ζ_2, as in the fracture shown in Sketch 3-5. The dike in the case of 3-3 blocks the flow and diverts fluids down to the container or, as in 3-4, acts as a more transmissive conduit, exposing waste encapsulated in the dike as well as waste in the container. Sketch 3-6 shows contaminant plumes resulting from these cases. These two cases are included here because the dike biases the initial conditions for release once the dike is cold. The possible choices for dike transmissivity are distinguished explicitly but should be left as a detail of the modeling.



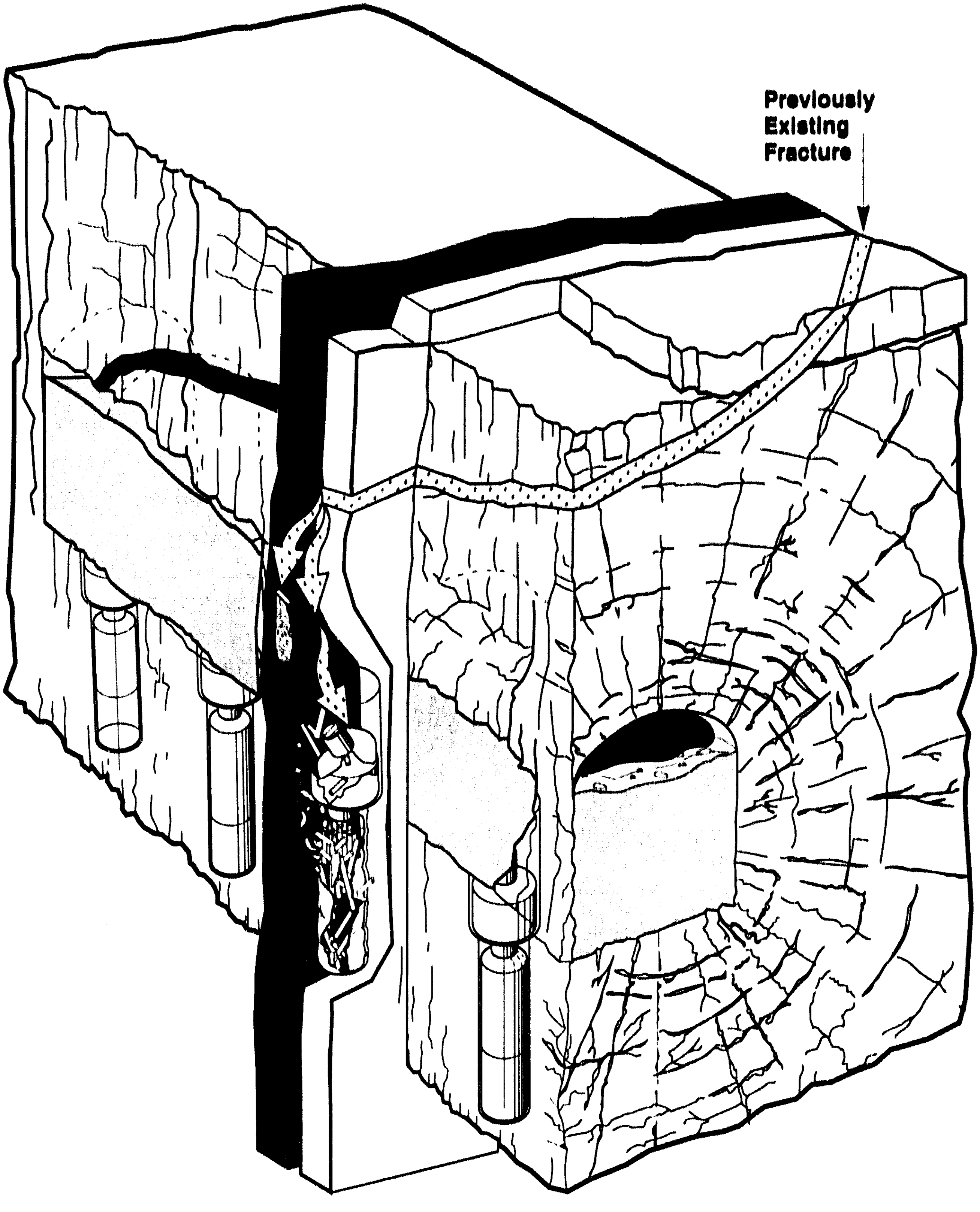
Sketch 3-2. Volatiles escape from damaged container and plate out in surrounding rock.



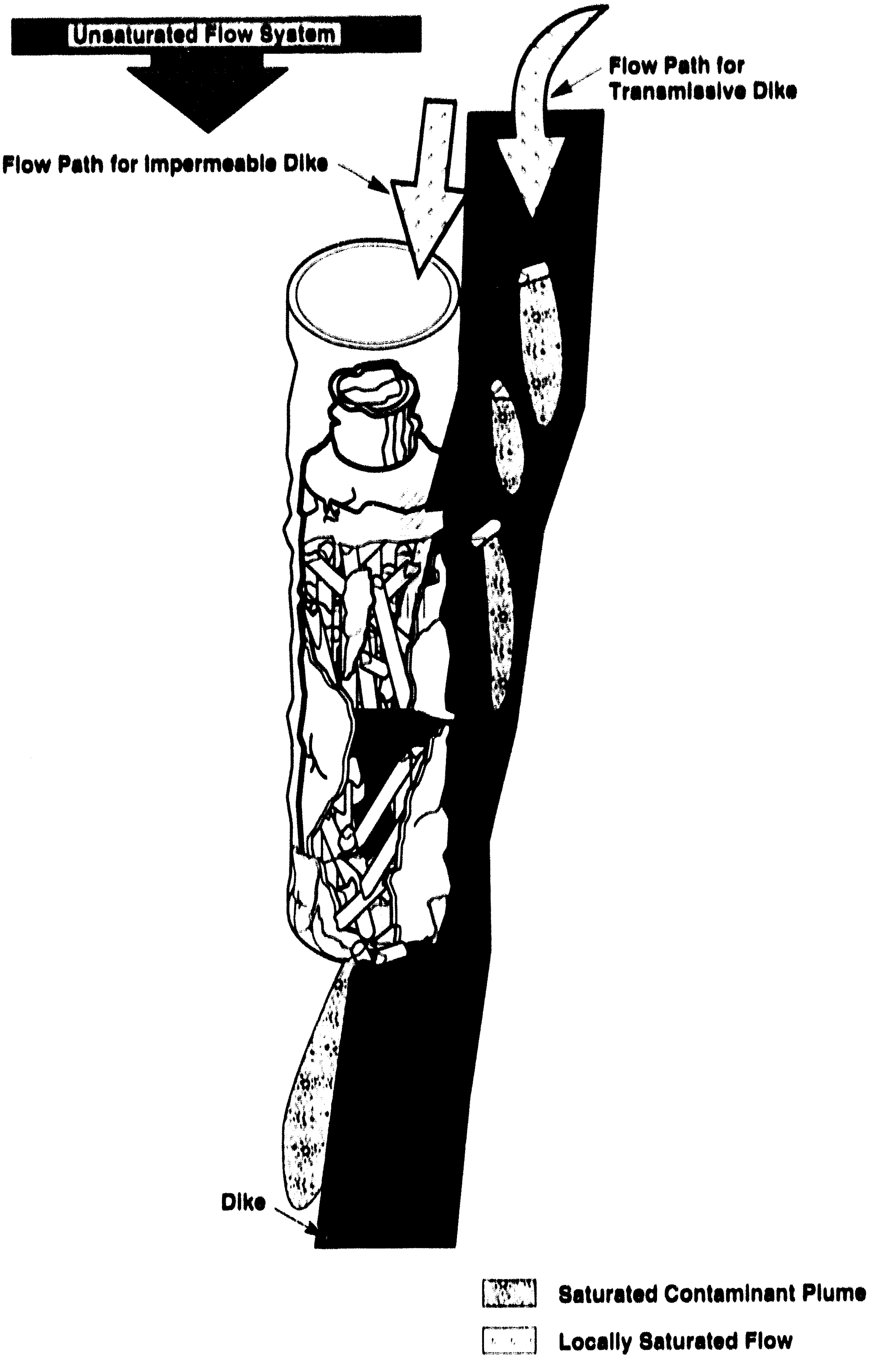
Sketch 3-3. As the vaporization isotherm regresses toward the container, condensed volatiles are exposed to hot fluids that mobilize condensed contaminants and transport them to the flow system.



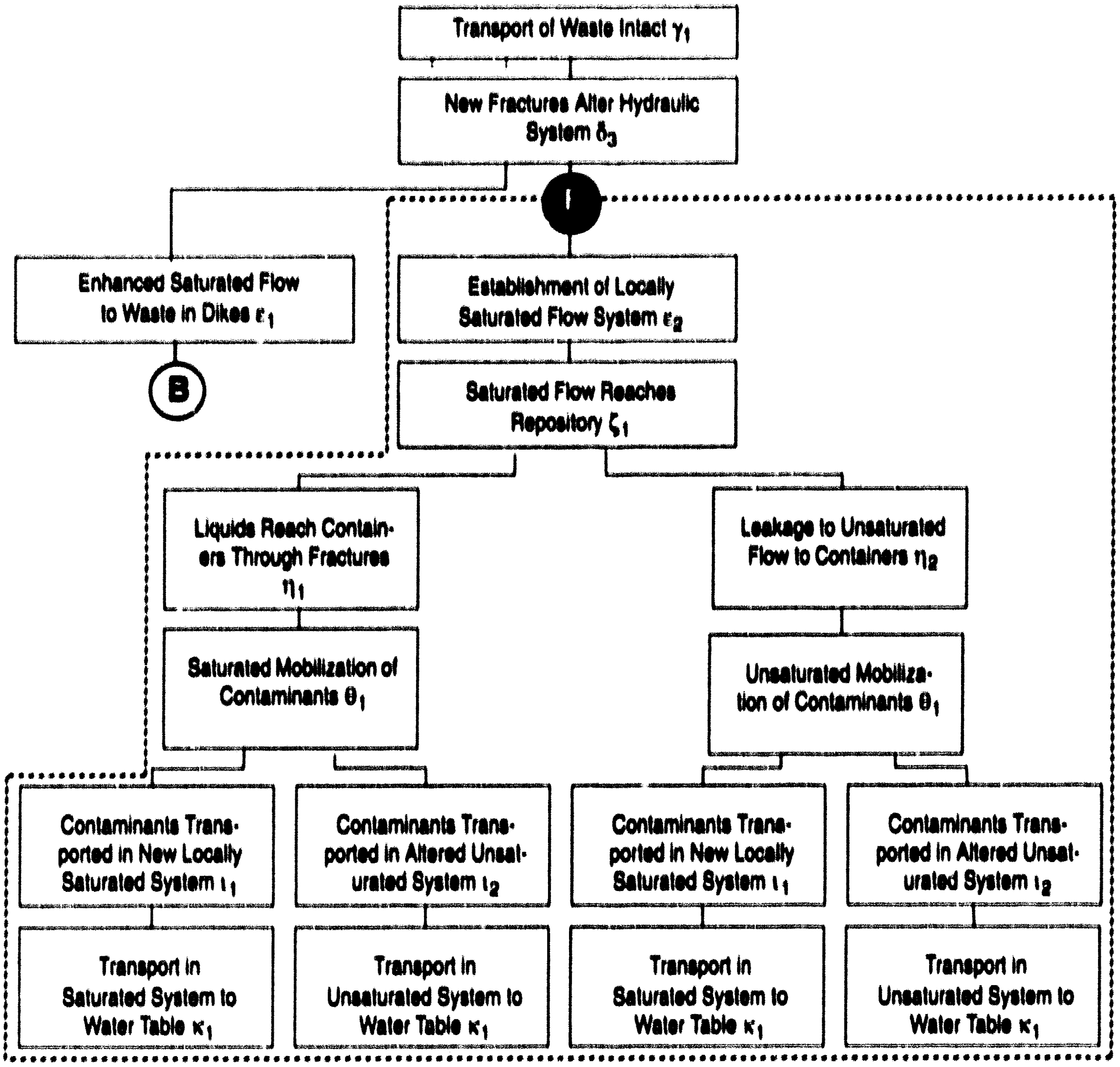
Sketch 3-4. Mobilizing of plated-out volatiles by reflux yields contaminant plumes that enter the unsaturated flow system.



Sketch 3-5. Previously existing fracture is cut by the dike, causing saturated flow along an impermeable dike or saturated flow within a transmissive dike.



Sketch 3-6. Saturated mobilization and transport in a locally saturated flow system along an impermeable dike or within a transmissive dike.

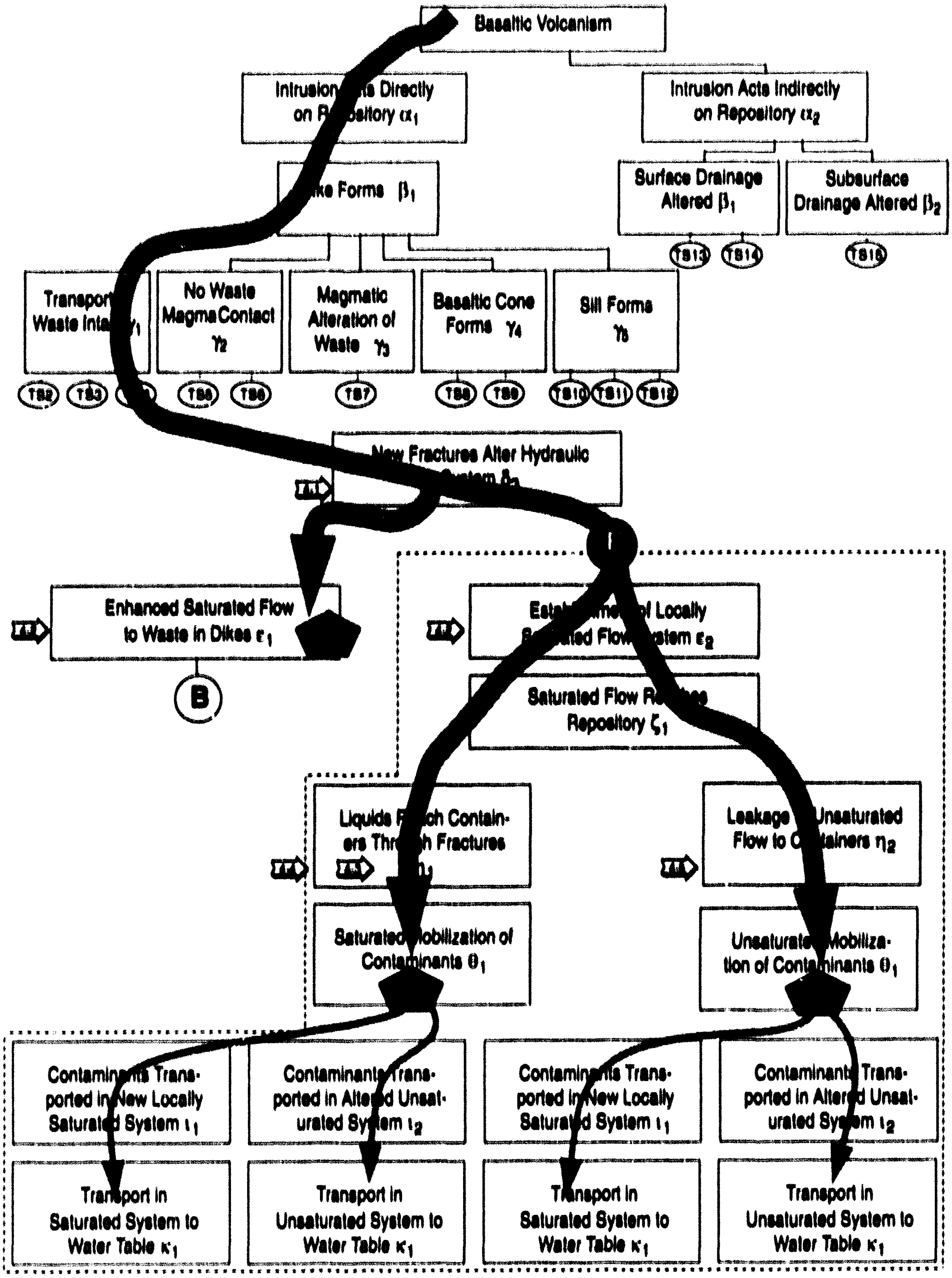


Tree Segment 4a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, transport of waste intact γ_1, new fractures alter hydraulic system δ_3.

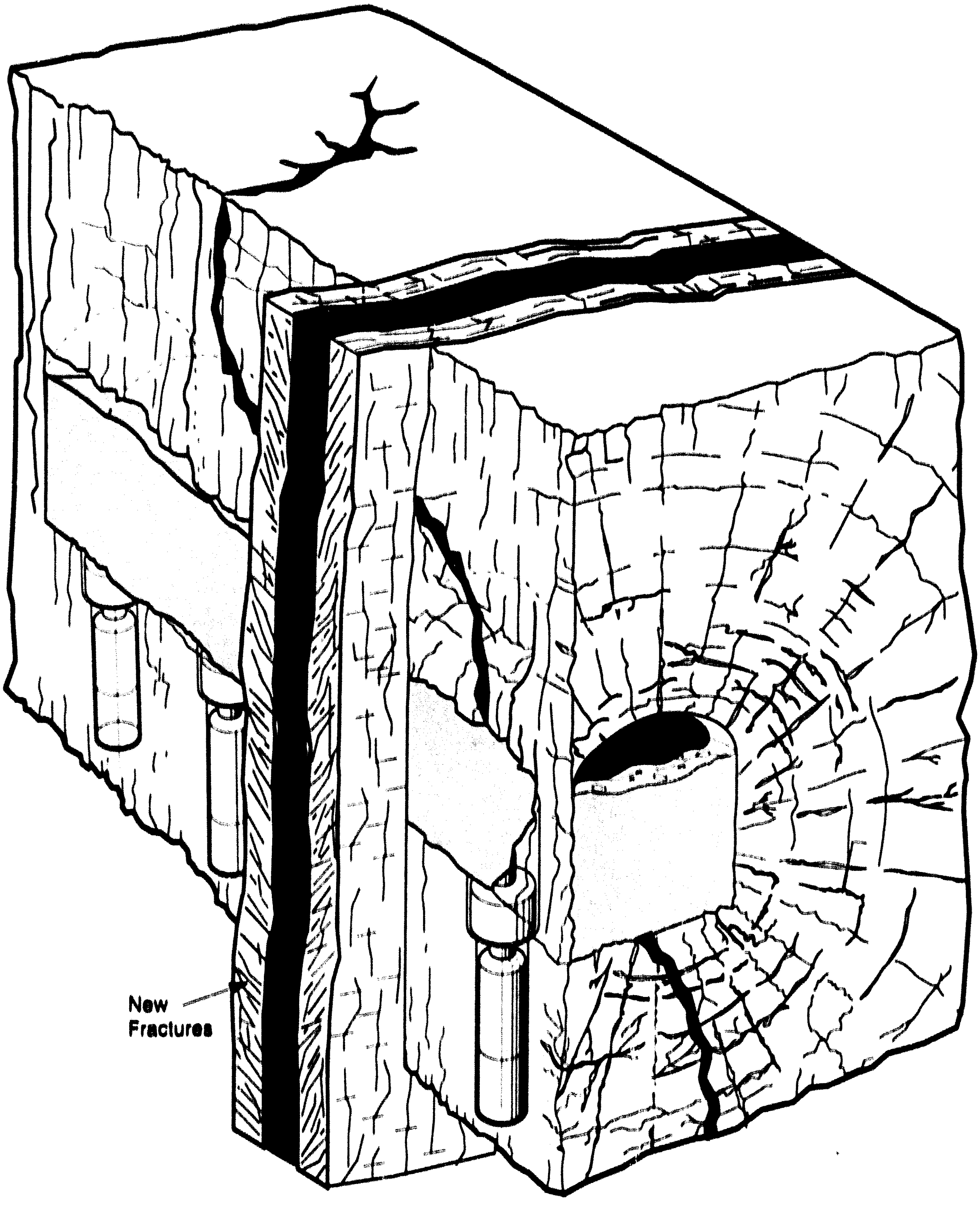
New Fractures Alter Hydraulic System (T84)

The intrusion, either by emplacement or during cooling, may produce a set of fractures in a zone adjacent to the dike and reaching out a few meters from it. This condition we refer to as **New Fractures Alter Hydraulic System** δ_1 (Delaney et al., 1986).

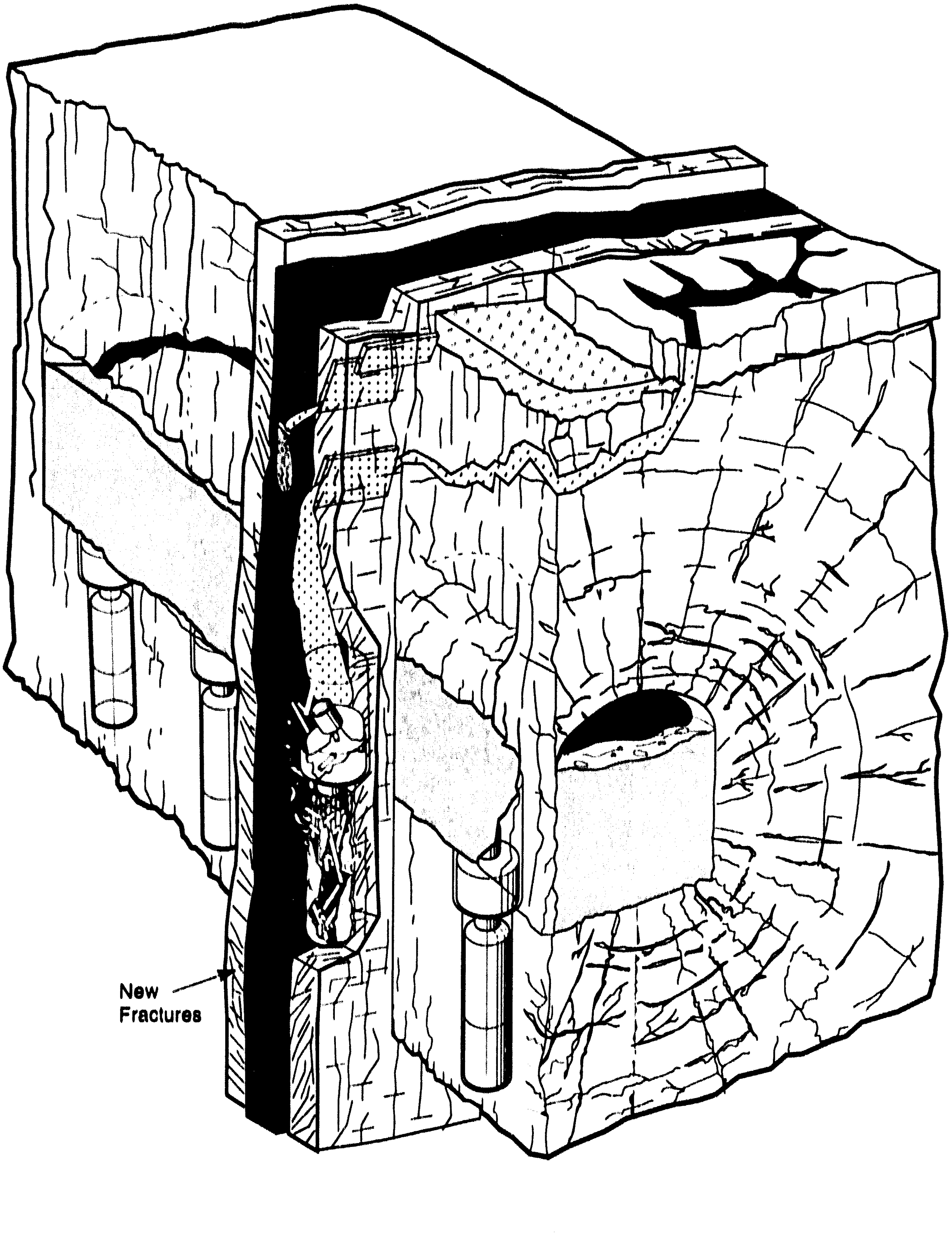
We presume that the hydraulic connectivity of these fractures suffices to alter the local hydraulic flow system. The new fracture sets, which occur in a zone adjacent to the dike, are shown in **Sketch 4-1**. **Sketch 4-2** shows interactions with the flow system as altered by the dike. These new pathways to the waste could provide a locally saturated source to the waste entrained in the dike, which we follow in 4-1; or, in 4-2, a fracture path to a container. In



Tree Segment 4b. Scenario paths and scenario group paths of tree segment 4a.



Sketch 4-1. During emplacement or cooling, the intruding dike causes fractures in a region adjacent to the dike and extending a few meters out from the dike.

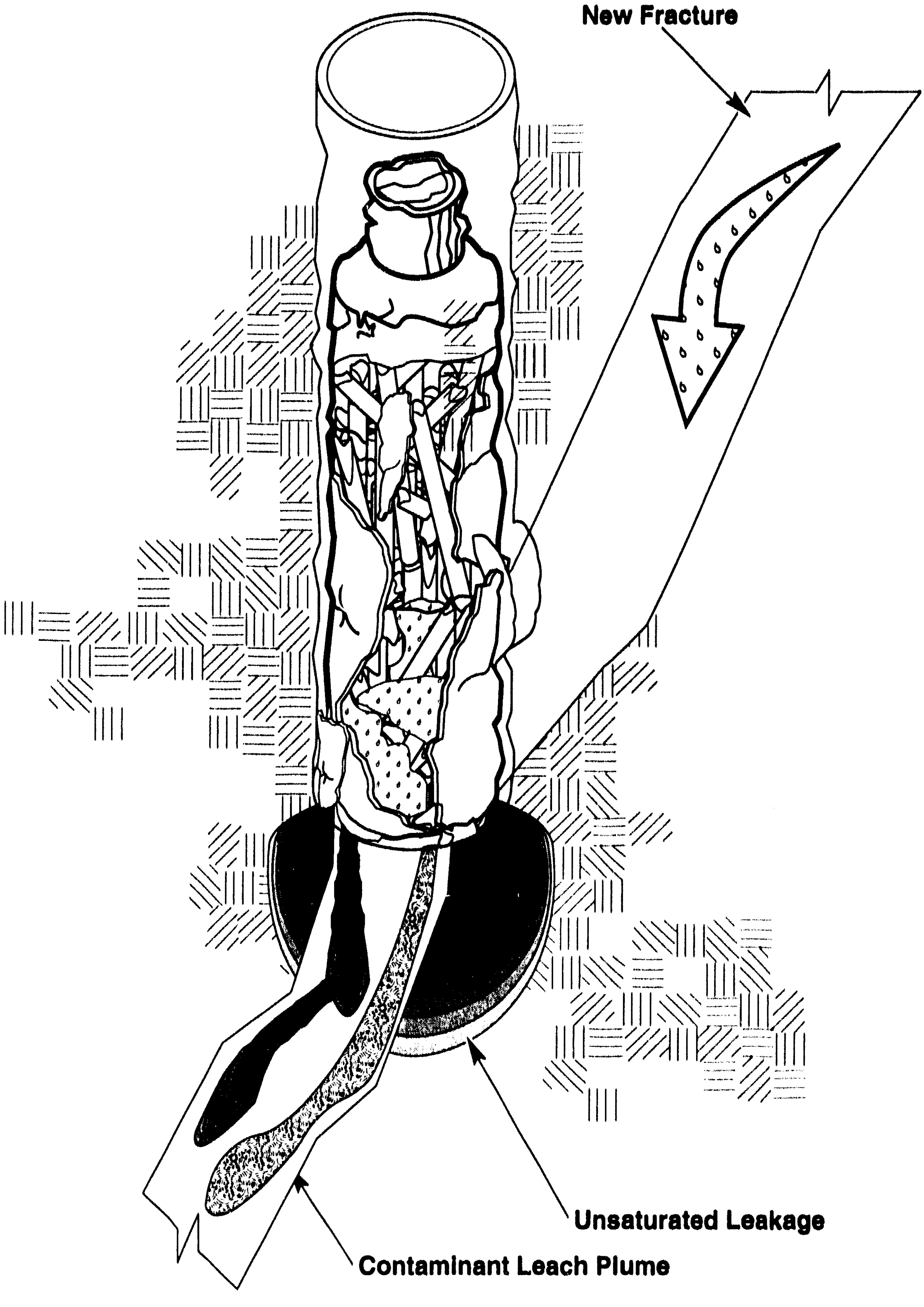


Sketch 4-2. New fracture sets adjacent to the dike provide greater continuity in water pathways.

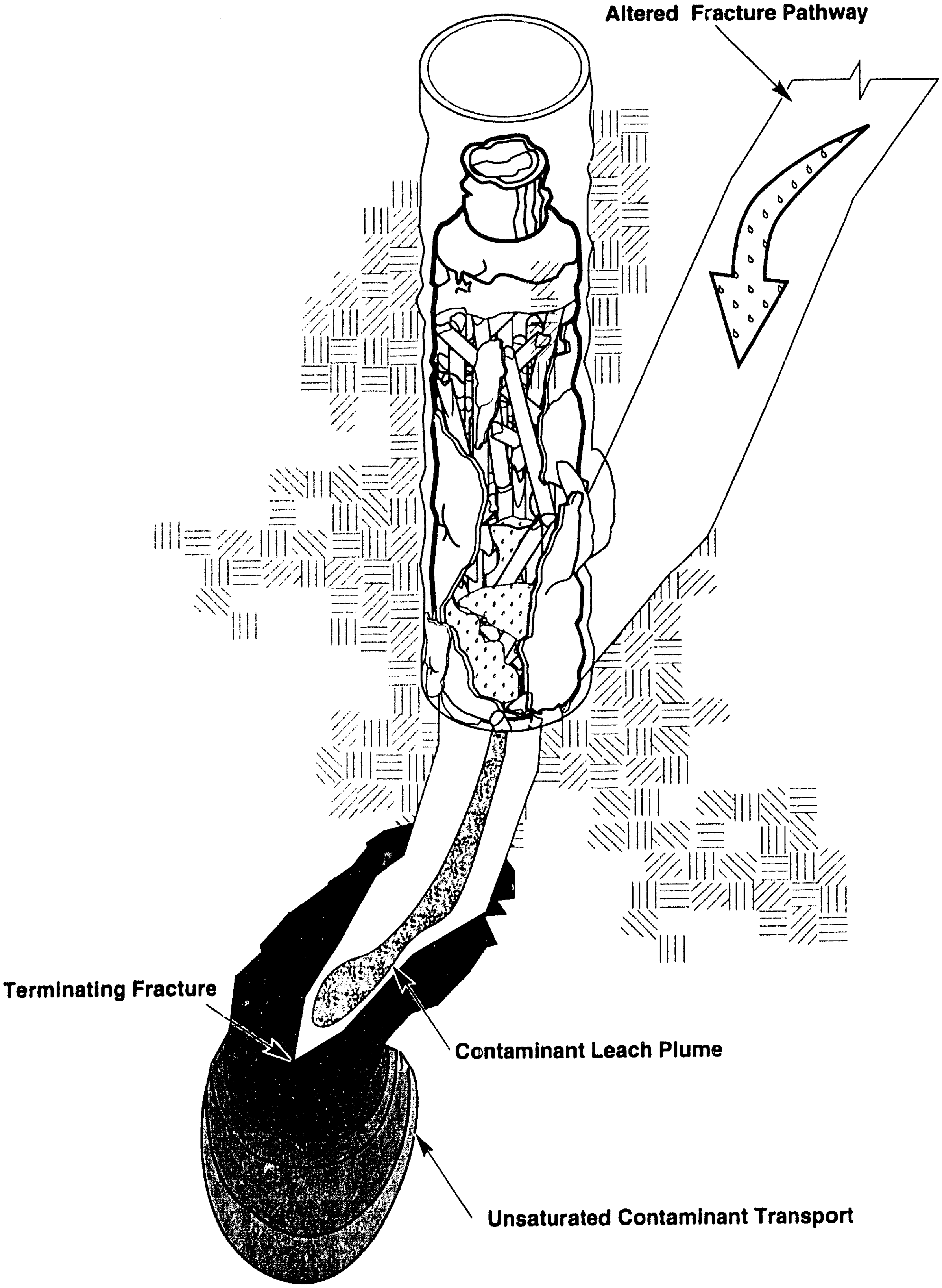
the path 4-3, the liquid is imbibed along the fractures near the waste (e.g., the terminating fracture in Sketch 4-5) and enhances unsaturated flow to the containers.

Details of some of the processes possible in the vicinity of a container are illustrated in Sketches 4-3, 4-4, and 4-5. The Tree Segment and Sketches illustrate some of the different physical processes bringing water to the container and spent-fuel debris, and reflect the fact that for a similar volume of water entering a fracture, the amount of fluid contacting the container and the duration of the contact are different. The continuation of each process whereby contaminants enter the flow system is also shown in these Sketches. If flow down a new fracture set reaches the container, saturated flow mobilization can occur as along 4-2, with the contaminants carried down the continuation of the fracture sets (Sketches 4-3 and 4-4) and acting as a source to either the saturated (Sketch 4-3) or unsaturated flow. If the fracture is blind as in Sketch 4-5, both mobilization of contaminants and transport to the water table occur in the unsaturated flow system.

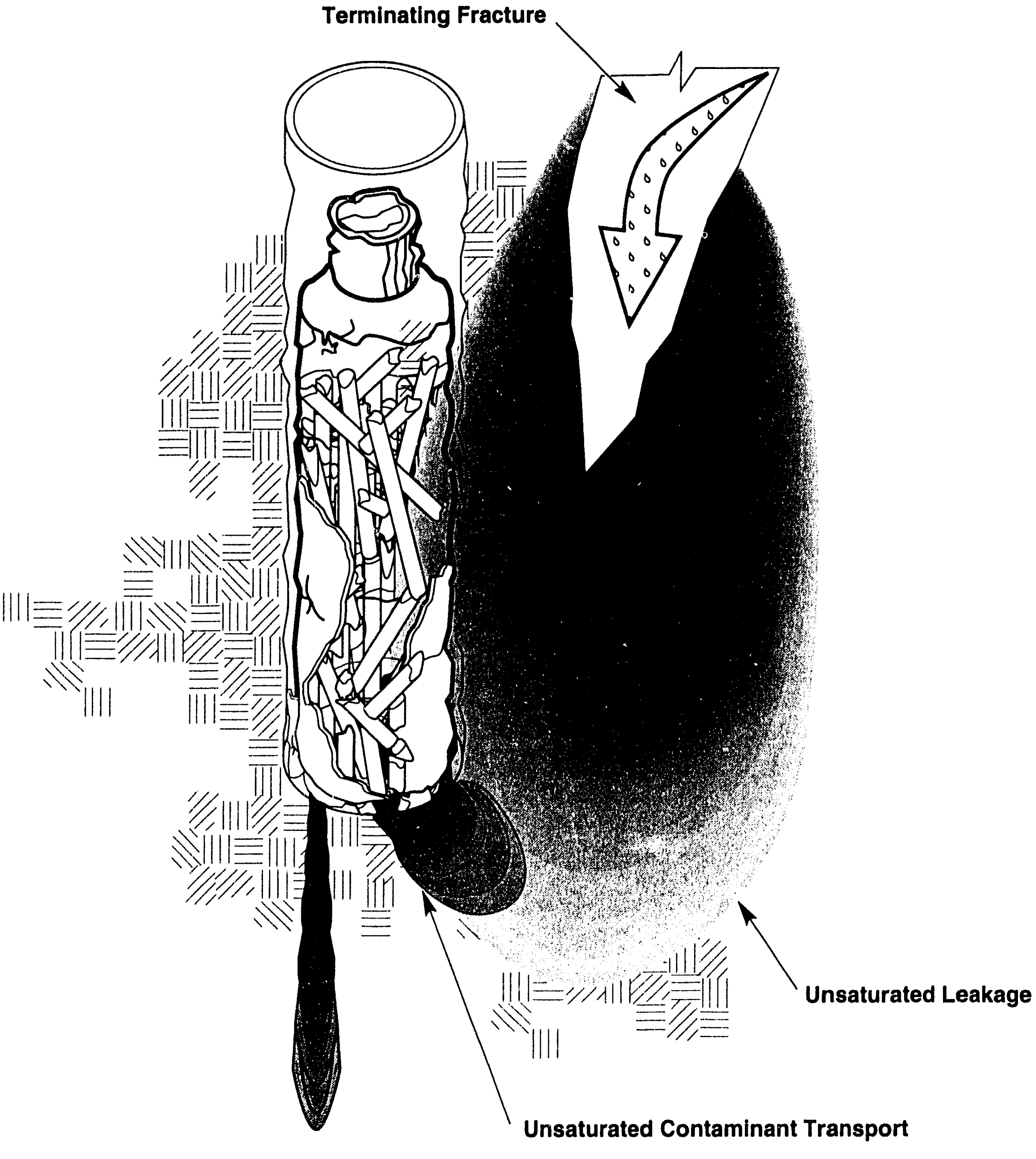
For a terminating fracture set that is carrying water, one expects movement into the matrix, with the matrix-fracture (composite model) system still carrying water to the container as in Sketch 4-5. Continuing along 4-3, we recognize that there could then be both unsaturated and saturated mobilization, producing contaminated fingers and contaminant movement into the leakage plume. In addition, the possible rapid movement in the contaminant plume because pores are saturated and fracture flow begins is explicitly included. Each of these three Sketches has several complicated flow interactions that must be analyzed.



Sketch 4-3. New fracture set allows enhanced flow to waste in container by increasing connectivity in the vicinity of the container.

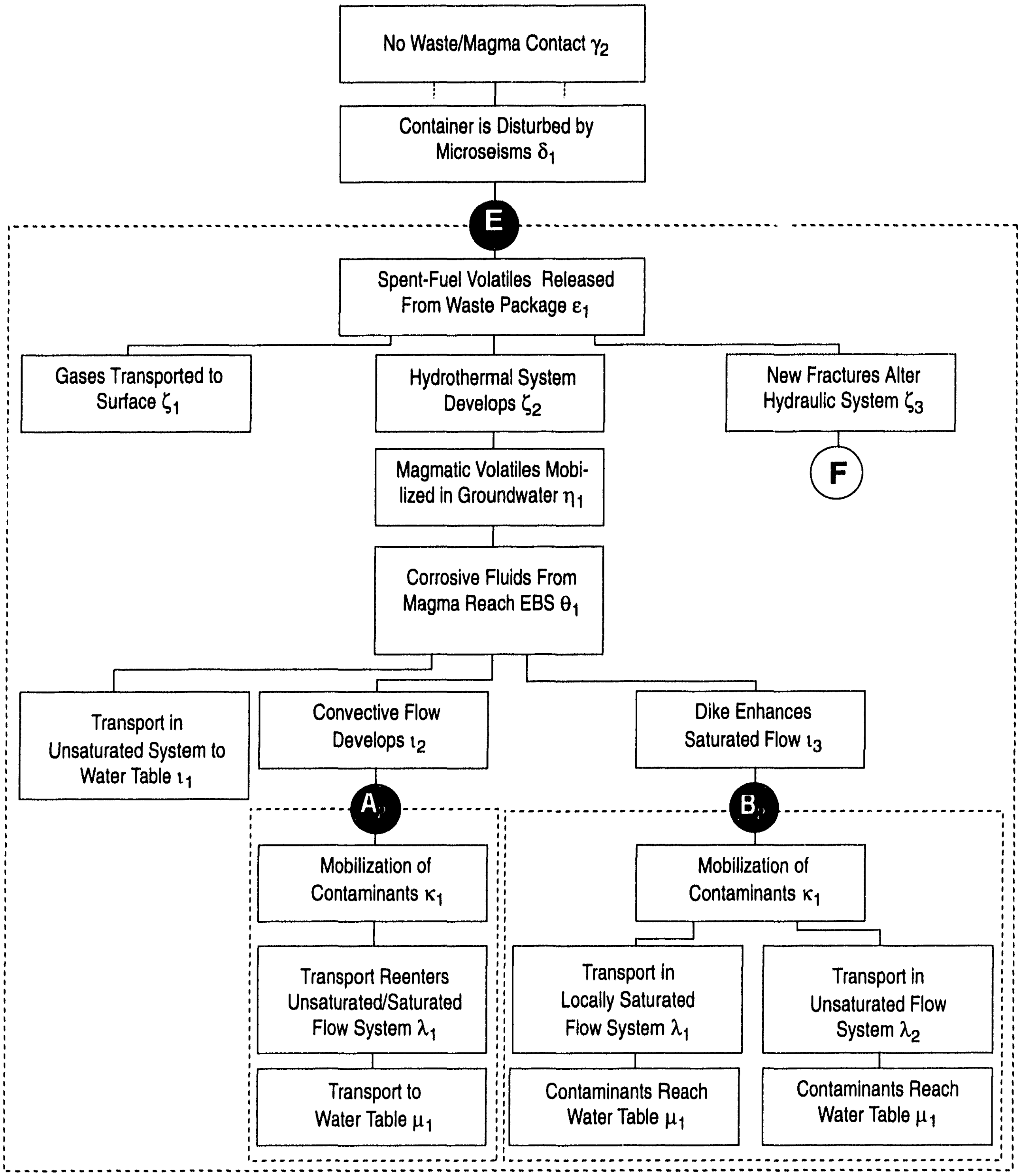


Sketch 4-4. Contaminants enter unsaturated flow system from new terminating fractures.



Sketch 4-5. A blind fracture acts as a source of enhanced unsaturated flow to a container.

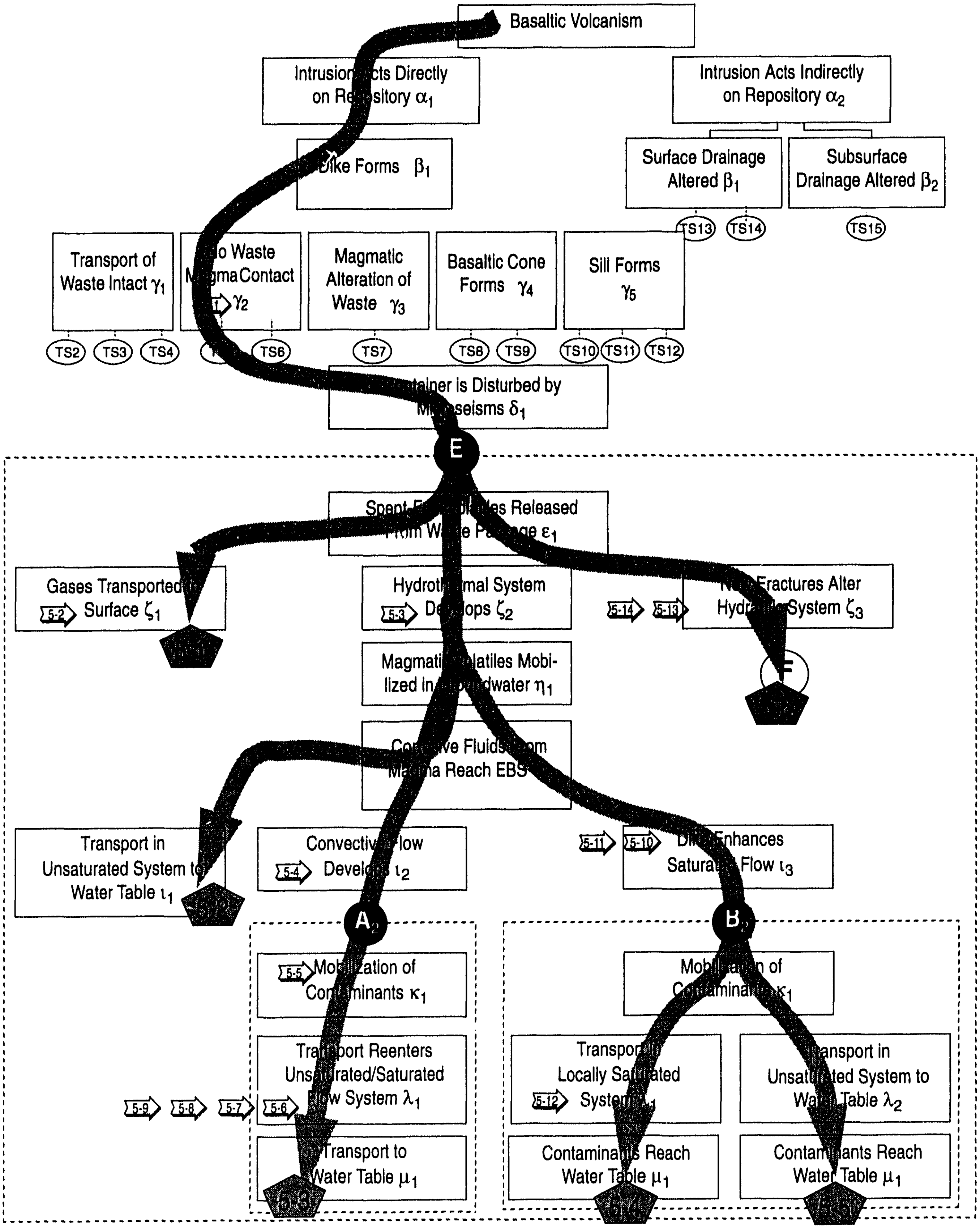
No Waste/Magma Contact ($\alpha_1, \beta_1, \gamma_2$)



Tree Segment 5a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, no waste/magma contact γ_2, container is disturbed by microseisms δ_1.

Container is Disturbed by Microseisms (TS5)

In the preceding discussion of the dike hitting containers, we only mentioned the existence



Tree Segment 5b. Scenario paths and scenario group paths of tree segment 5a.

of thermal and mechanical effects the neighboring containers would see. These effects are similar to those that would occur if the intruding dike hit no containers. Referring to the event tree, we find such effects on by-passed containers in a branch called No Waste/Magma Contact γ_2. Tree Segment 5a is the expansion of the Container is Disturbed by Microseisms δ_1 branch of No Waste/ Magma Contact γ_2.

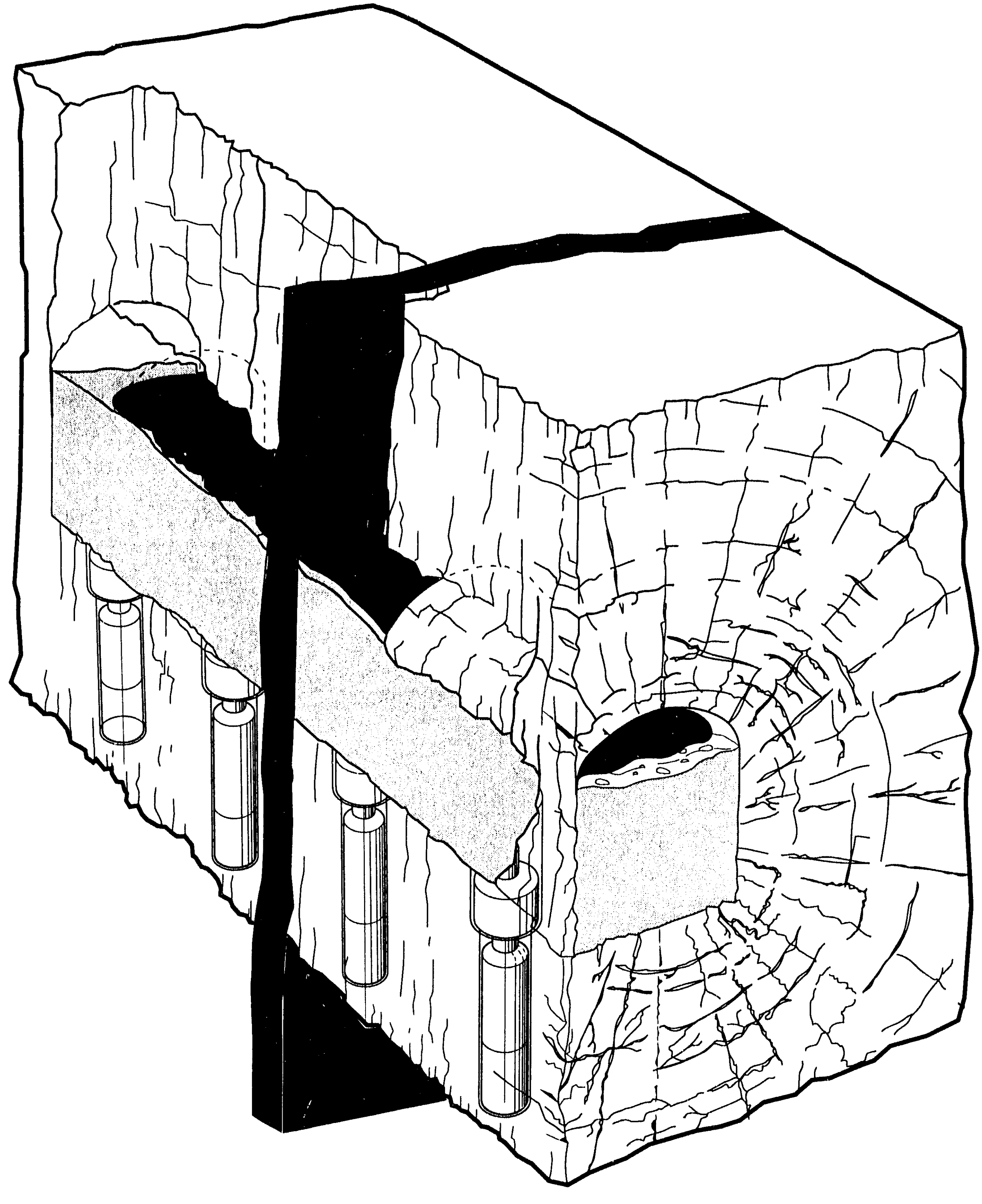
In this branch, containers are not physically contacted by the intrusion, as shown in Sketch 5-1. An intrusion on the scale we are discussing is likely to have been accompanied by microseisms continuing for weeks or perhaps months. While freshly emplaced containers, which are hardened for shipping, might be infrequently damaged, the same cannot be said for aging containers. The reader is reminded of the possible states of the container shown in Sketch 2-3. It should be noted that an important specification in a calculation will be the condition of the spent fuel. When the fuel rods are damaged and broken, fuel will spill. As a function of burnup, the state of this fuel will be expected to vary from fuel pellets to lumpy sand, with the latter state more common as burnup is increased. In Sketch 2-3, the center container points to a specific problem that may occur even for pristine containers. That problem is cracking of the container due to the banging about in the hole. This becomes a matter of concern to calculations because the cracks provide a path for spent-fuel volatiles to escape to the rock.

There may be three populations of contaminants available to be transported: gaseous compounds escaping to the surface, spent-fuel volatiles that have condensed outside the container, and those radioisotopes still in the remains of the container. The escaping gases, plate-out volatiles (both those that have left the damaged or aged remains and those on the interior surfaces of a sound container), and solid remains are all included in Sketch 5-2.

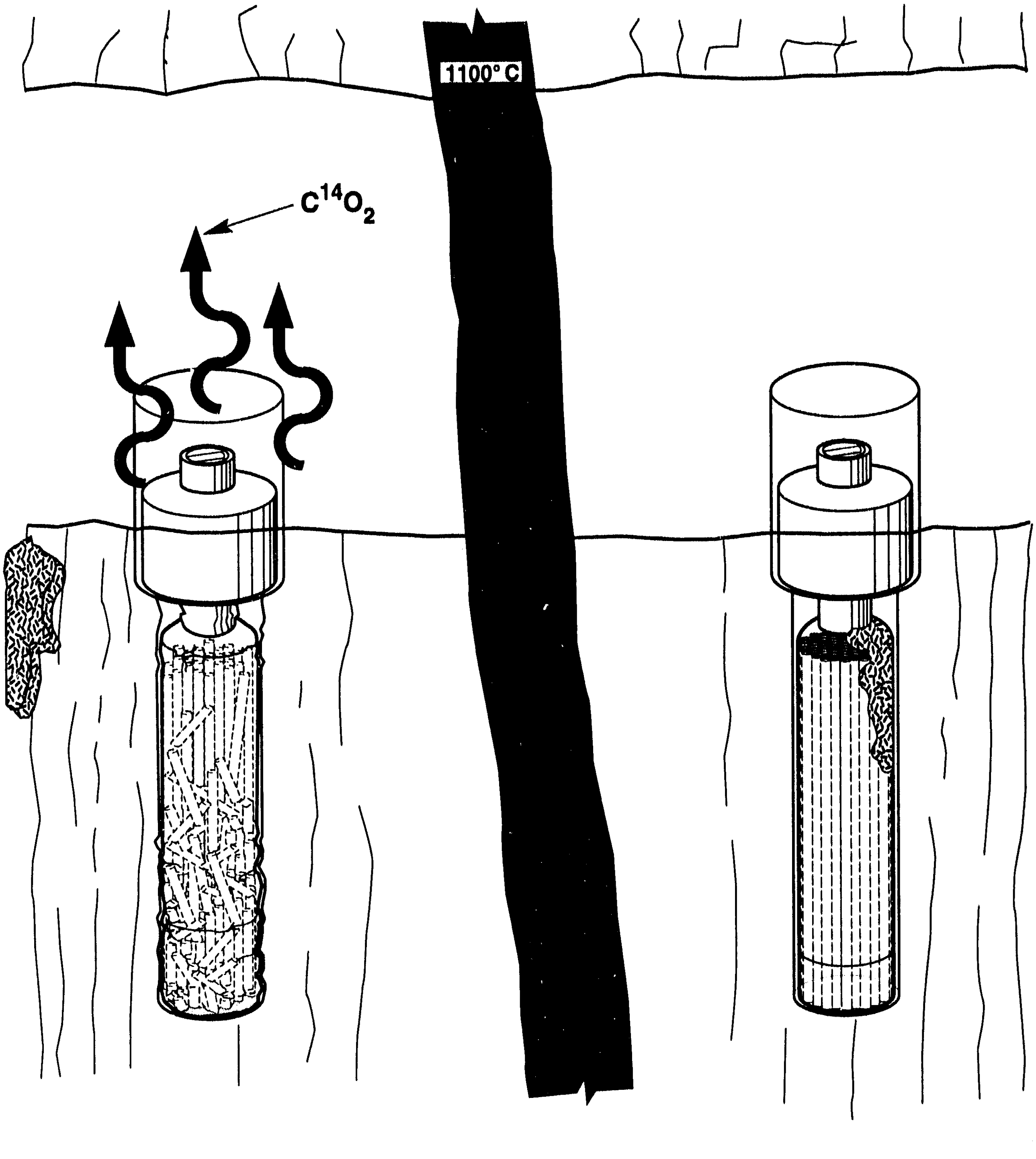
5-1 allows for release of gaseous compounds from the ruptured container. Supporting calculations and models for this scenario have already been constructed and analyzed by various workers (Light et al., 1990; Zwahlen et al., 1990; Ross et al., 1992; Van Konynenburg et al., 1985). This leaves the influence of the thermal field and of the alteration of the strain field to be discussed.

Tree Segment 5b includes four scenario paths, 5-2 through 5-5, for thermally driven flow as shown in Sketch 5-3. In this group of scenarios, intrusion of molten basalt heats its neighborhood, causing dryout close to the dike and perhaps a couple of meters out. Two-phase convection occurs from the water table up, supplying vapor and hot water to the containers. The boundary of the region experiencing the dryout and convection moves rapidly outward from the dike and then moves more slowly inward to the dike over a year or two. Added to the vapor phase are any magmatic volatiles being exsolved or outgassed by the intrusion. There is a possibility of a saturated flow refluxing past containers located further away from the dike. How many containers are exposed is a matter for calculation. The system we are describing is time varying and many details arranged in the tree in a sequence are, at times, occurring simultaneously and will be modeled simultaneously. Sketches 5-4 through 5-12, presented in this section, suggest modes of mobilization and transport and are applicable not only to one or more of these branches, but also to branches discussed in other sections of this report.

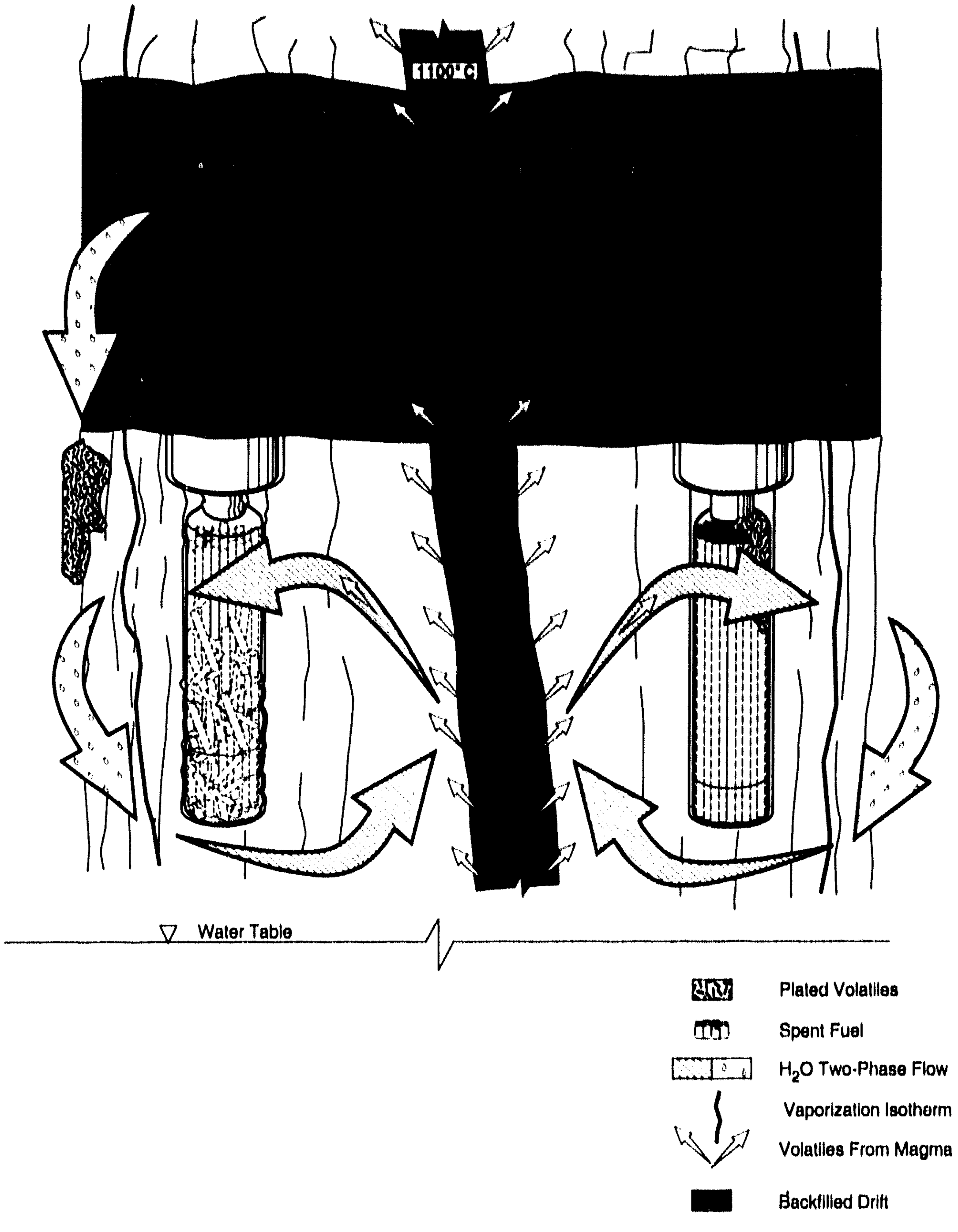
5-2 is the branch Transport in the Unsaturated System to the Water Table, which occurs for a relatively cold dike. As the flow system is re-established around the dike, one expects the plated-out radionuclide volatiles to be the first at risk for further transport. Sketch 5-4 is a possible interaction of these plated-out spent-fuel volatiles with the flow system as the volatilization zone re-



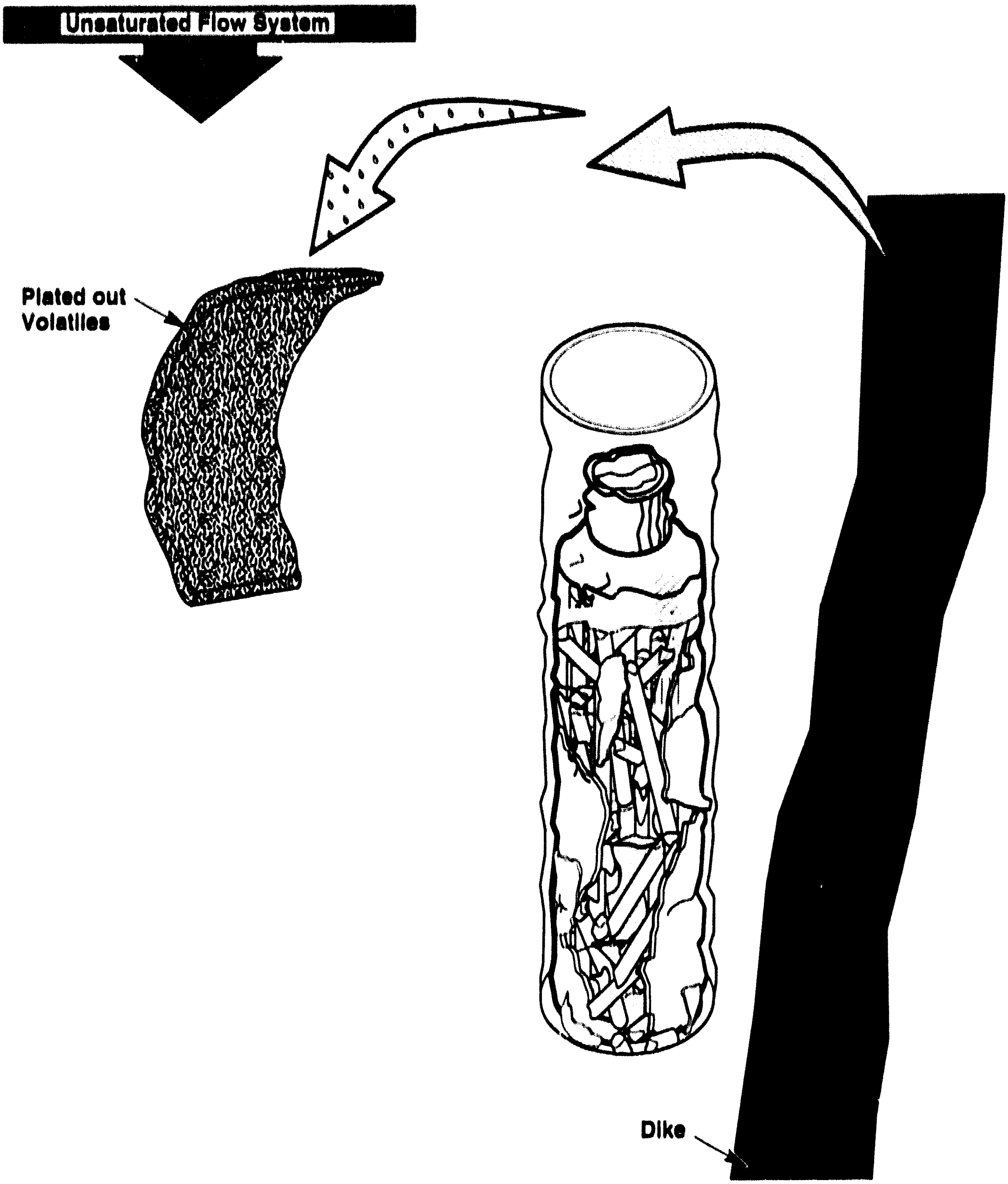
Sketch 5-1. Dike intrudes potential repository without contacting containers.



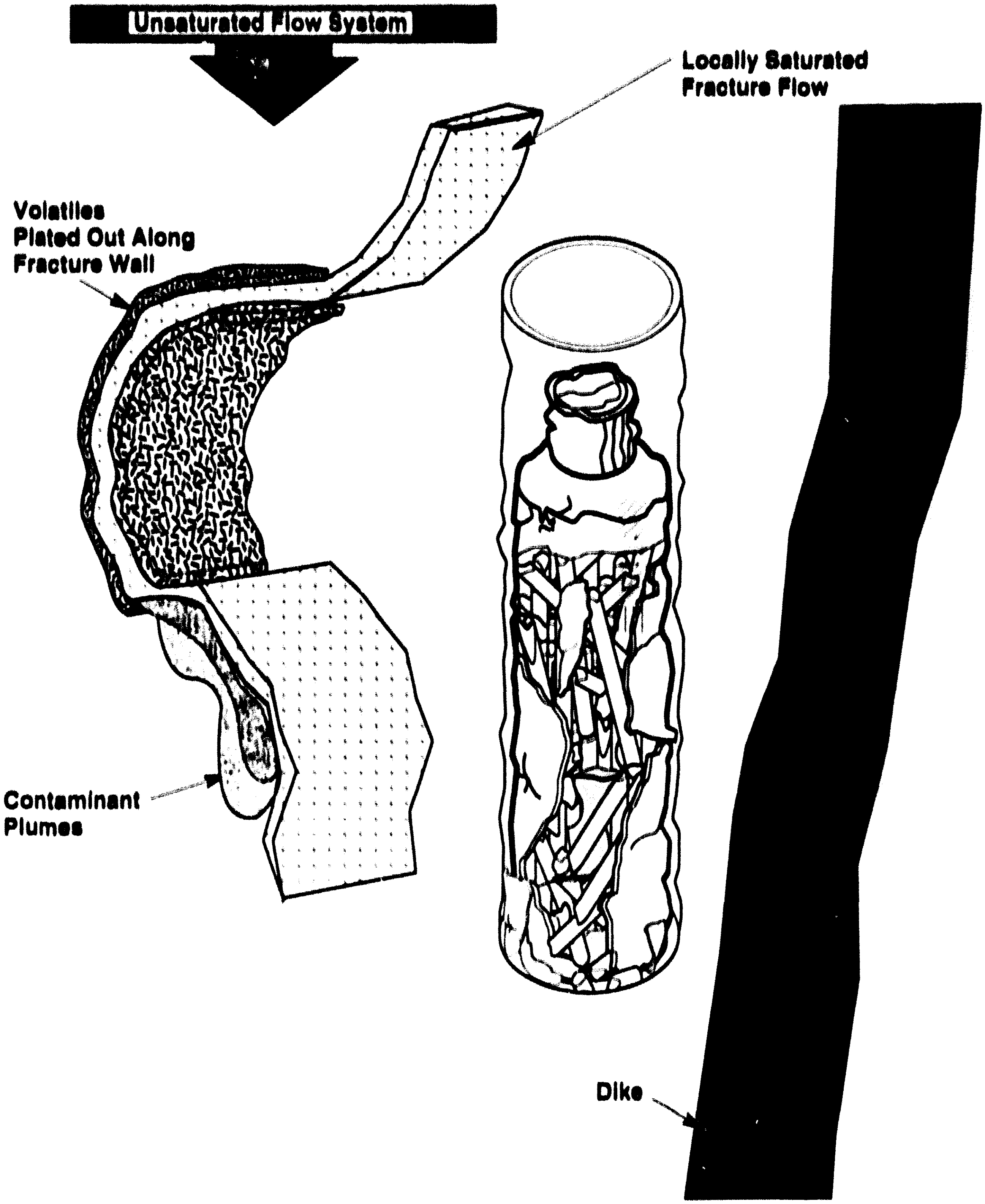
Sketch 5-2. Spent-fuel volatiles exit waste through gaseous escape, plate-out in rock surrounding containers, or plate-out within intact containers.



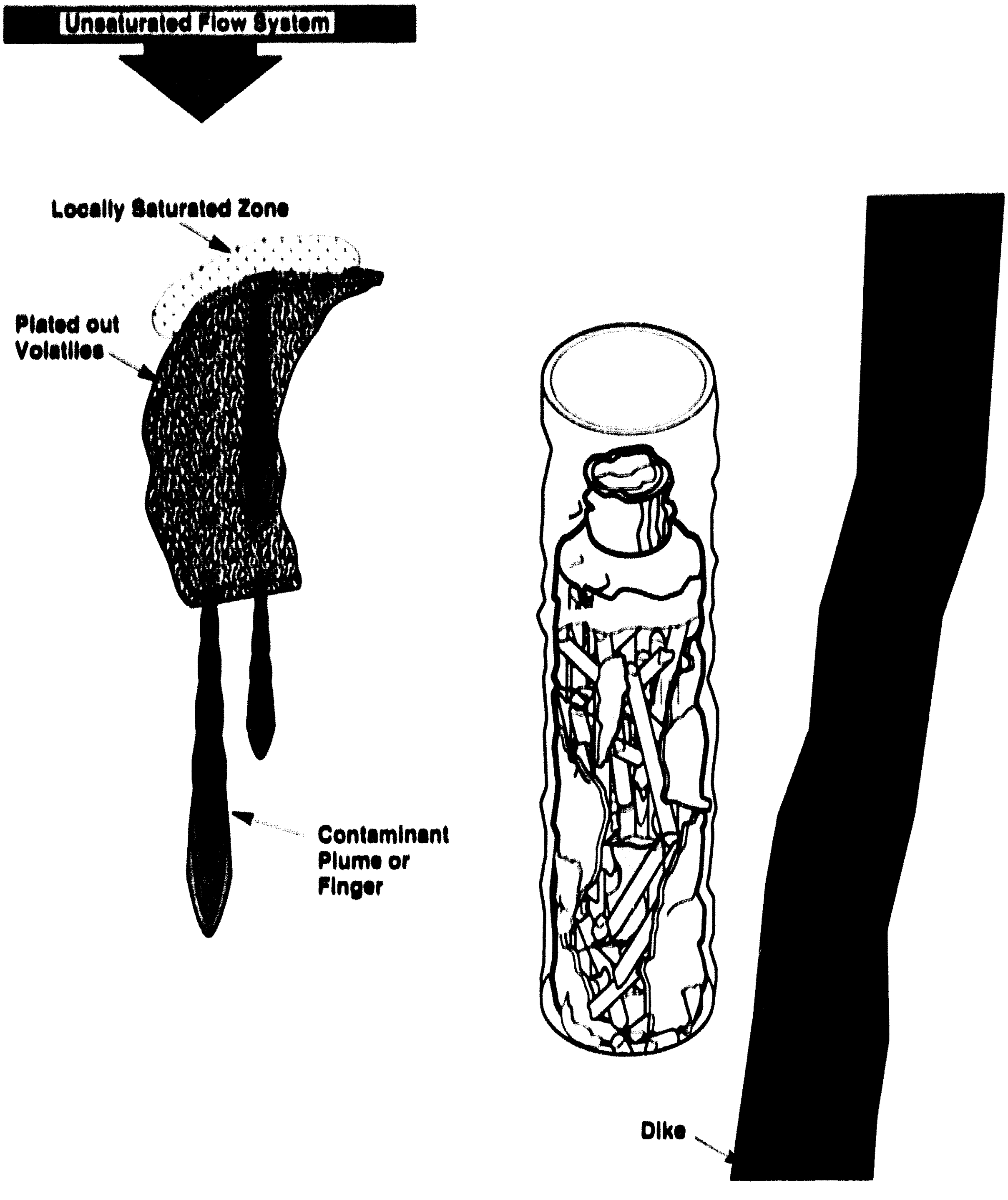
Sketch 5-3. Components of waste are exposed to magmatic volatiles, including water vapor, outgassed from the intruding dike.



Sketch 5-4. Reflux of the two-phase convective flow exposes plated-out spent-fuel volatiles to enhanced fluid flow.



Sketch 5-5. Mobilization and transport of plated-out contaminant in a locally saturated fracture flow system.



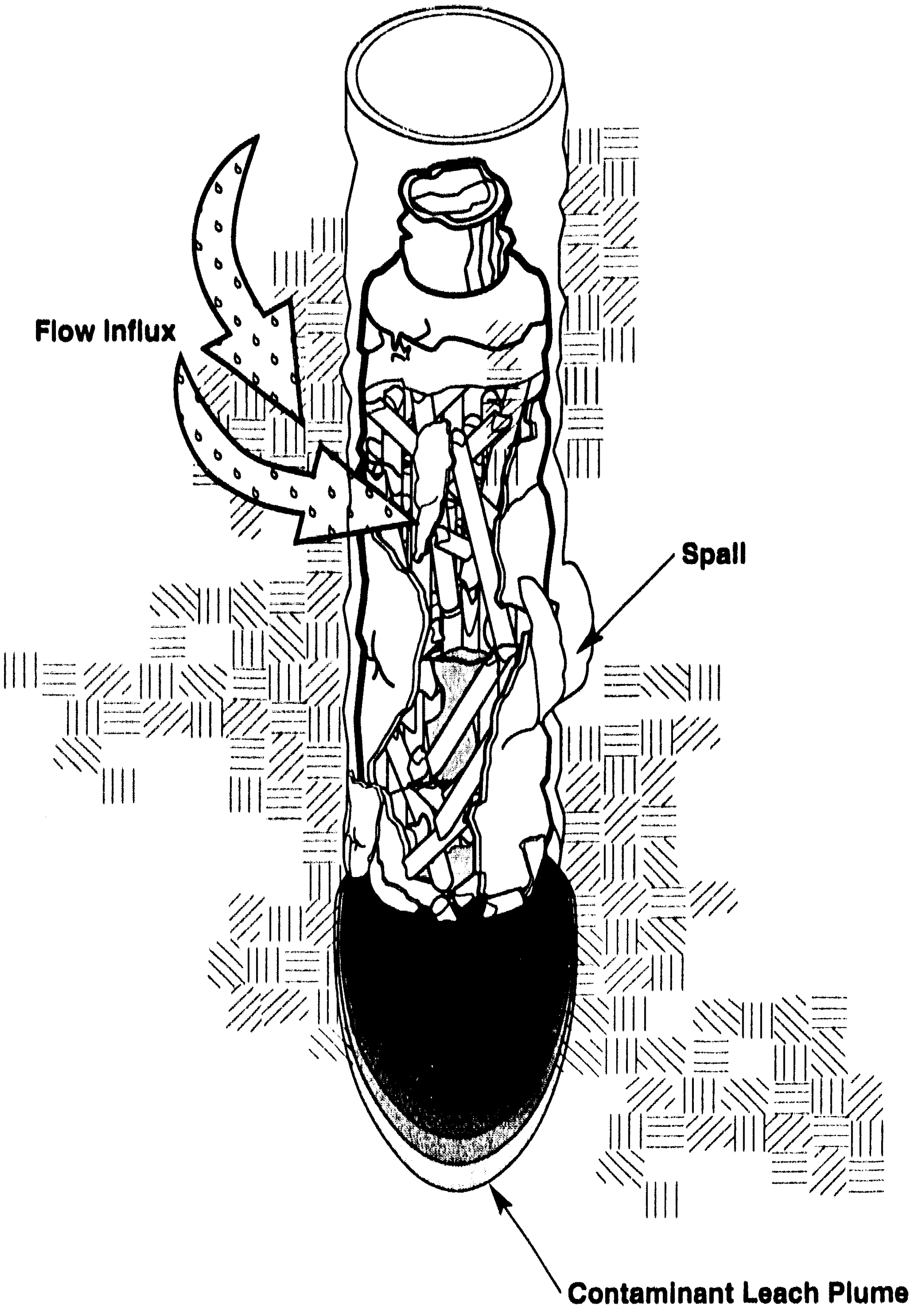
Sketch 5-6. Saturated mobilization of plated-out spent-fuel volatiles and their transport in the unsaturated flow system by fingering.

tracts toward the dike and saturated reflux reaches a plate-out zone. Sketch 5-5 is a case where the plate-out occurs along a fracture. As the vaporization isotherm permits, locally saturated flow resumes, resulting in contaminant mobilization plumes that may eventually enter the unsaturated flow or the saturated flow system. Sketch 5-6 shows a locally saturated region above a plate-out region responsible for reducing permeability of the affected rock. Subsequent mobilization occurs and contaminants again enter the unsaturated flow system. Mobilization of plated-out spent-fuel volatiles was also mentioned in conjunction with Sketches 3-3 and 3-4.

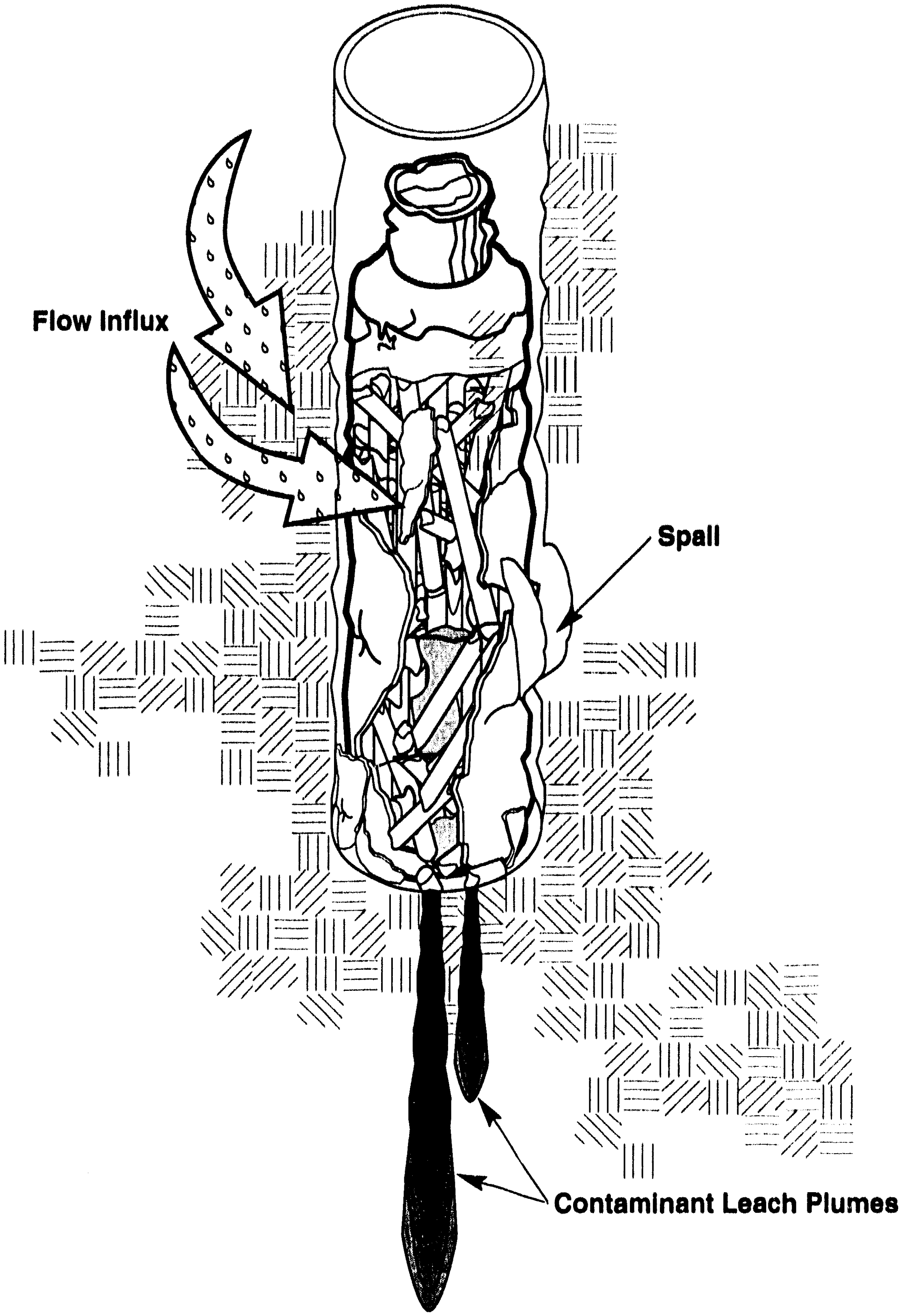
Along path 5-3 we surmise that during the few years the dike is hot enough to drive convection, a two-phase convective flow may occur. Related details suggested in Sketch 5-3 show a two-phase convection that develops around the dike for the few years of thermal excursion during cooling, and reflux of the two-phase convection, which contributes to mobilization of plate-out and of containers away from the dike. As the dike cools, containers closer to the dike are affected. It should be noted that the water table may act as a source for this convection. Its participation needs to be included in any models. Details to consider regarding mobilization and transport to the water table, involving both unsaturated and saturated flow, are suggested in Sketches 5-7, 5-8, and 5-9. As the neighborhood of the dike cools further, material in the containers (or the container remains) is available to the flow field.

Another contribution to consider along the path including No Waste/Magma Contact γ_2 and Container Disturbed by Microseisms δ_1, is the effect of the dike on any saturated flow to and from the EBS. We refer to 5-4 and 5-5. These scenarios proceed as 5-3 to where the dike alters the flow system. There are two alterations indicated in Sketch 5-10: interception of a locally saturated flow system (e.g., fracture flow) and ponding caused by blockage of lateral diversion in an unsaturated flow field. In the first case, interception of a locally saturated flow system, we anticipate immediate dryout to some few meters into the rock; the fluid is able to return to the vicinity of the dike only after the dike has cooled. The steam produced in dryout will simply join that flowing upward from unsaturated zones. It is possible for a cold dike to have substantial fracture permeability; in that case the dike would be a conduit protecting the waste from contact. We see no detrimental effect and therefore disregard this possibility. In the case that the dike is a sufficient barrier to flow to cause the fluid to seek other fractures leading downward, we presume there are adequate connections around the drift and through the stress-altered region to reach containers. The number of containers at risk depends on the lateral extent of the fracture system. Sketch 5-11 illustrates the effects of the second alteration, ponding due to blockage of lateral unsaturated flow. In the case of local saturation, the matrix fills and the fractures, in the sense of the composite model of Peters and Klavetter (1988), carry the excess. This in effect provides locally distributed, saturated flow to containers. The case in which the fracture is blind with no direct connection to a container is included in this case. Sketch 5-11 shows yet another mobilization mode implicit in the diversion caused by the dike. Blocked diverted flow has filled the matrix and initiated fracture flow (composite model), which reaches the container emplacement hole and might partially fill the hole. Contaminants are mobilized from the debris in the hole and are transported by fingering into the unsaturated flow system, possibly coalescing into a plume. Fingers and the plume are presumed to transport contaminants to the water table.

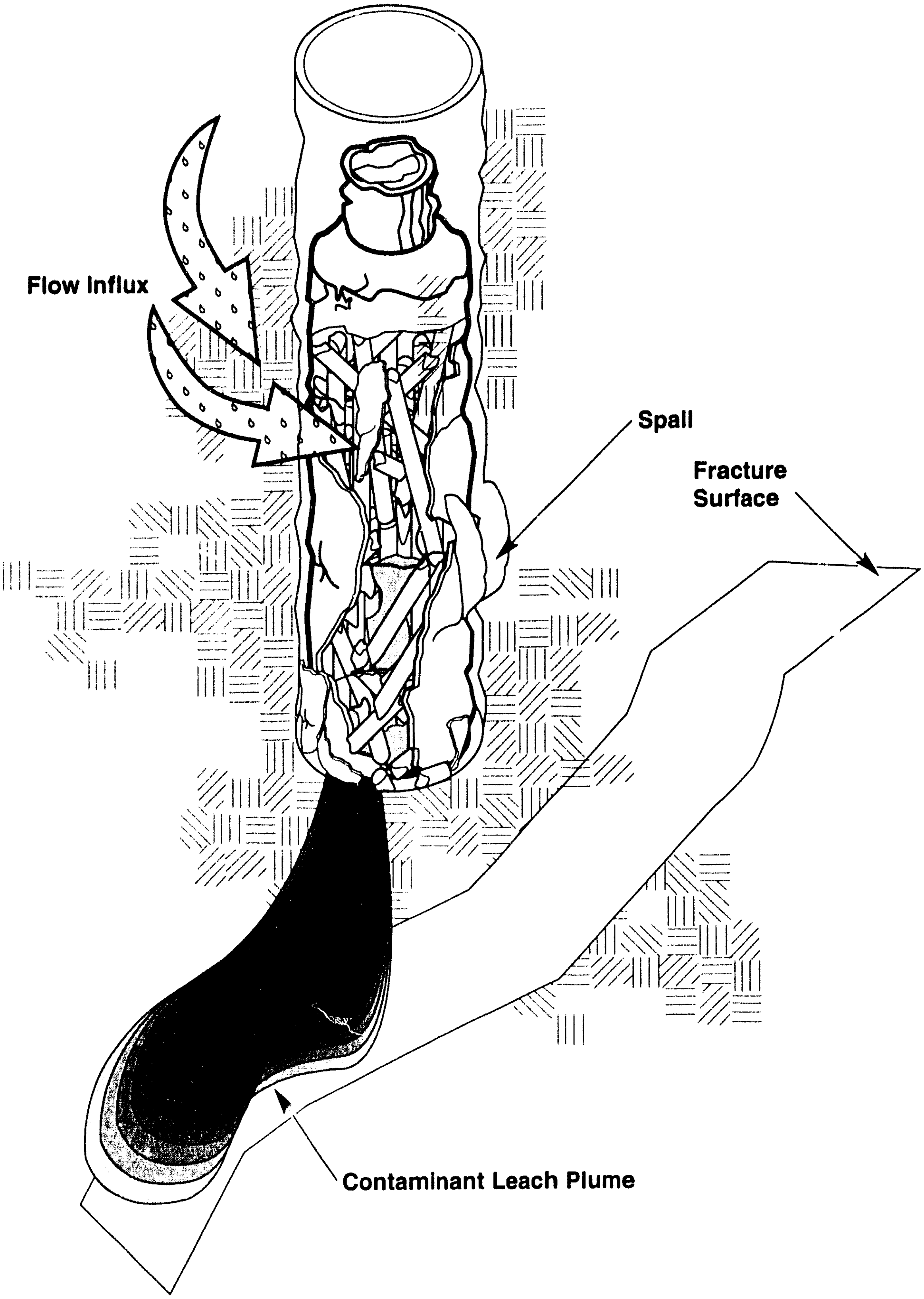
Sketch 5-12 illustrates interception of a container hole by a macroscopic fracture (or fracture set), providing a pathway to a container. Mobilization takes place in the emplacement hole, which is partially filled with liquid. The leachates are then presumed to leave the hole both



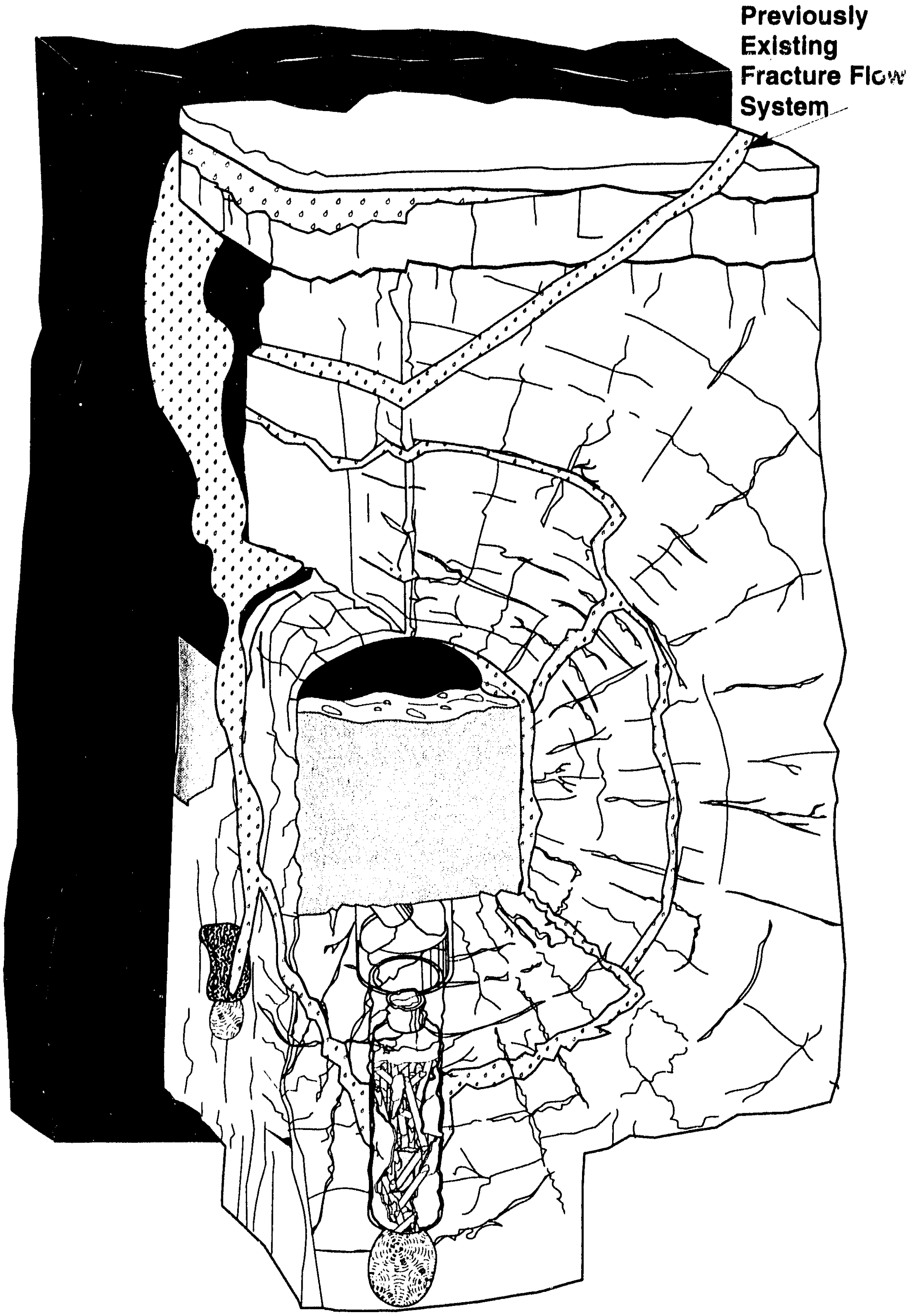
Sketch 5-7. Unsaturated mobilization and transport.



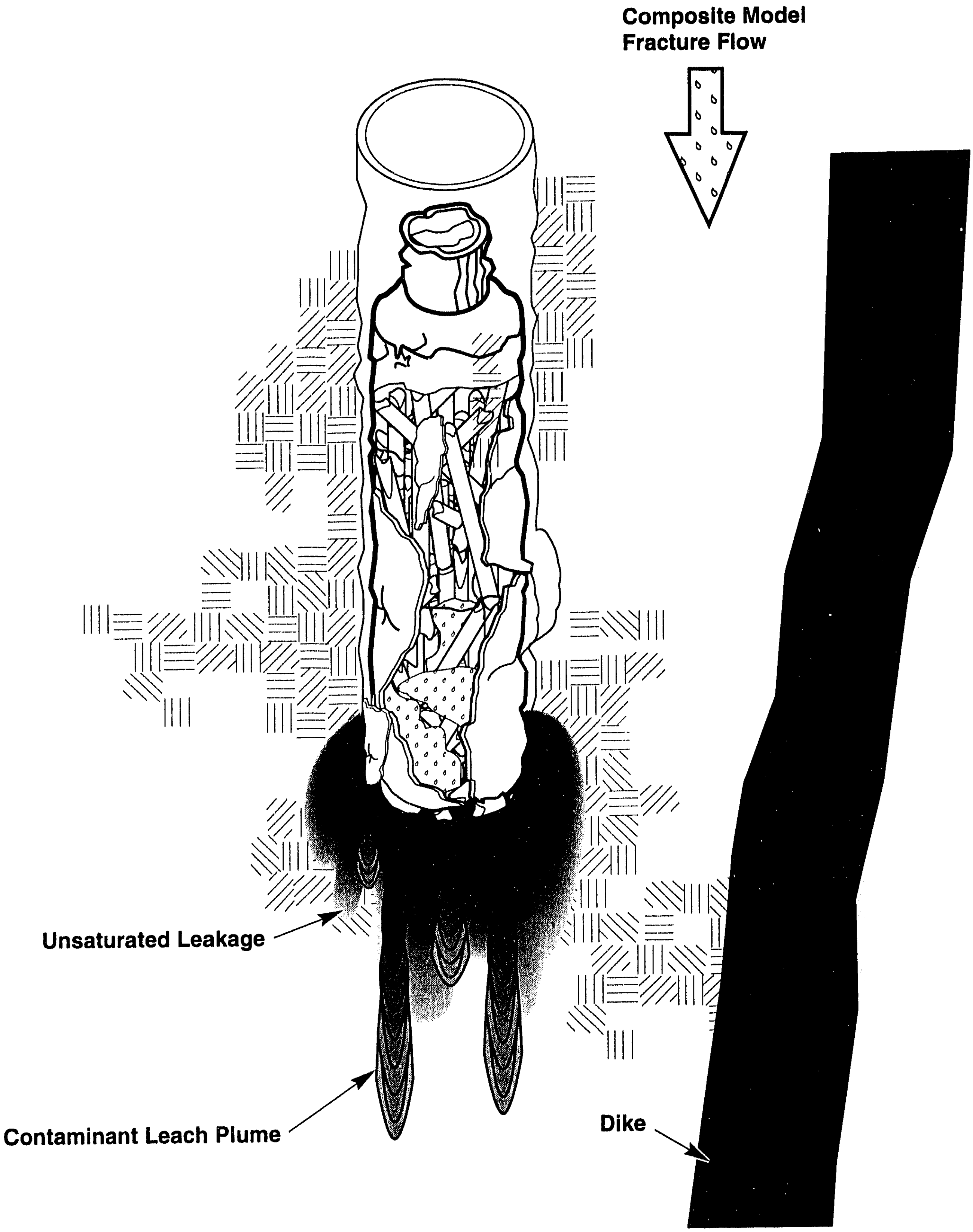
Sketch 5-8. Unsaturated mobilization with transport by fingering phenomenon.



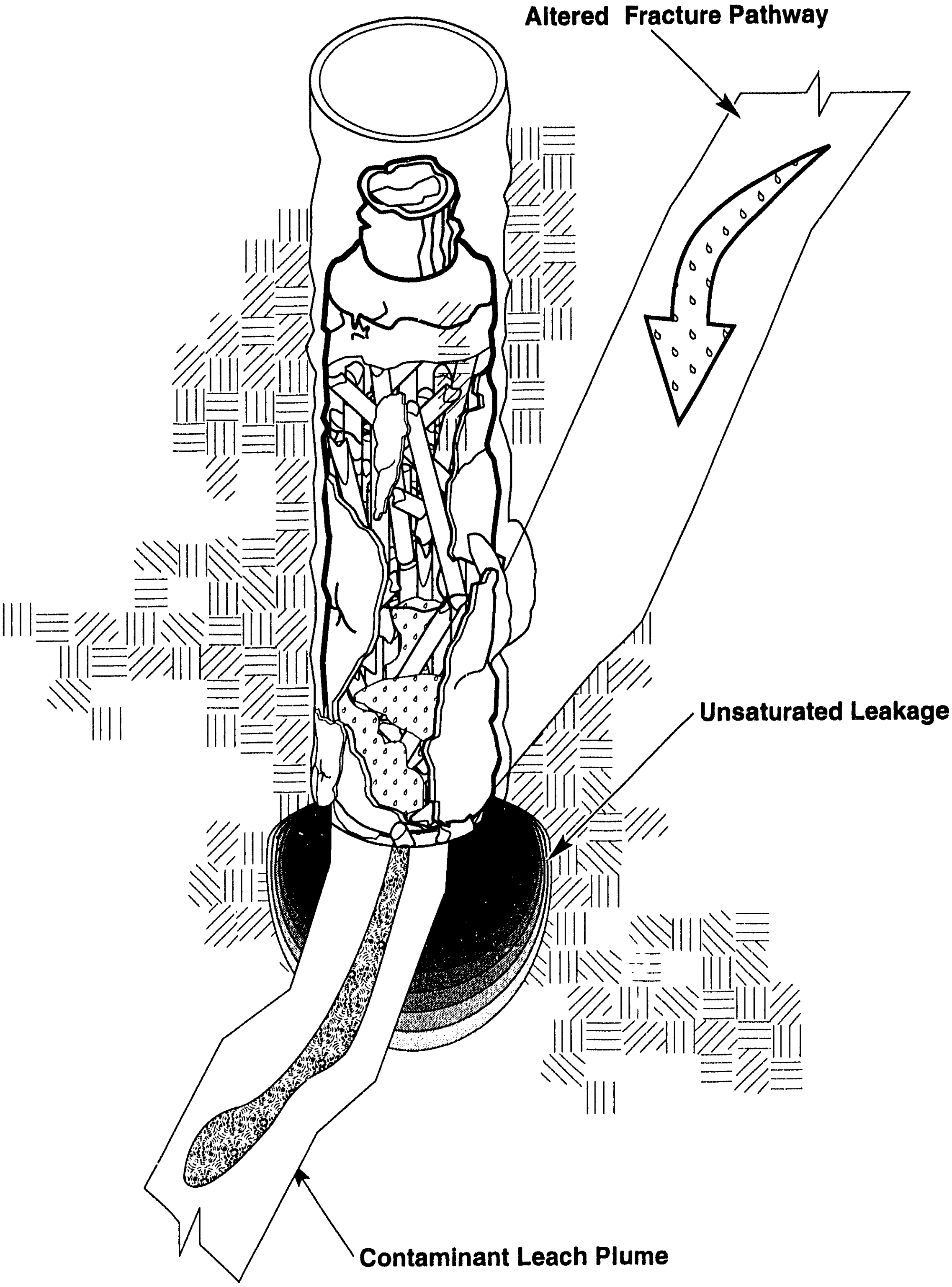
Sketch 5-9. Saturated mobilization and transport of contaminants.



Sketch 5-10. Dike blocks lateral flow to cause ponding and intercepts pre-existing fracture flow.



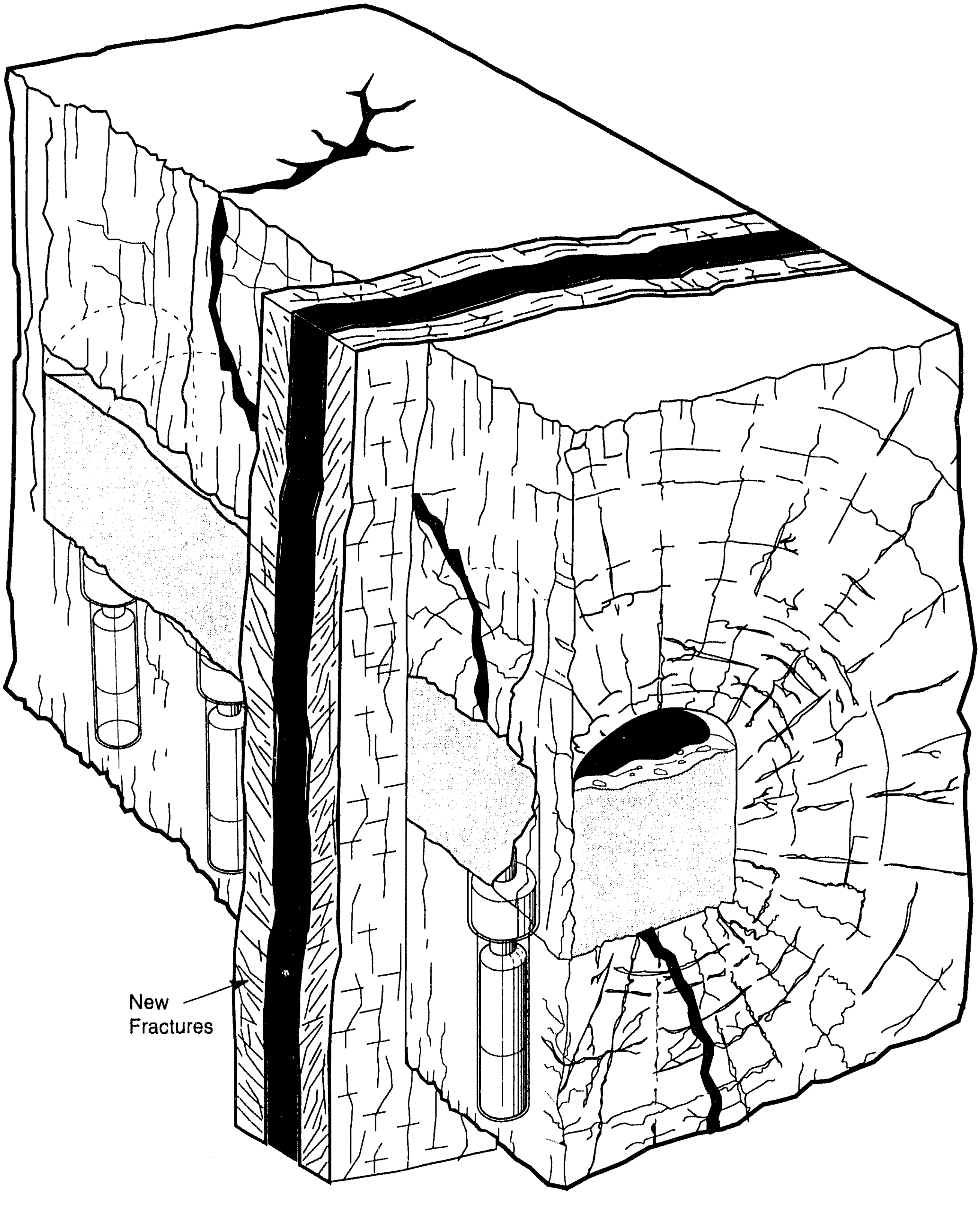
Sketch 5-11. Locally saturated flow (composite model) is diverted to a container by an impermeable dike. This diversion results in mobilization and produces contaminant plumes in the unsaturated flow field.



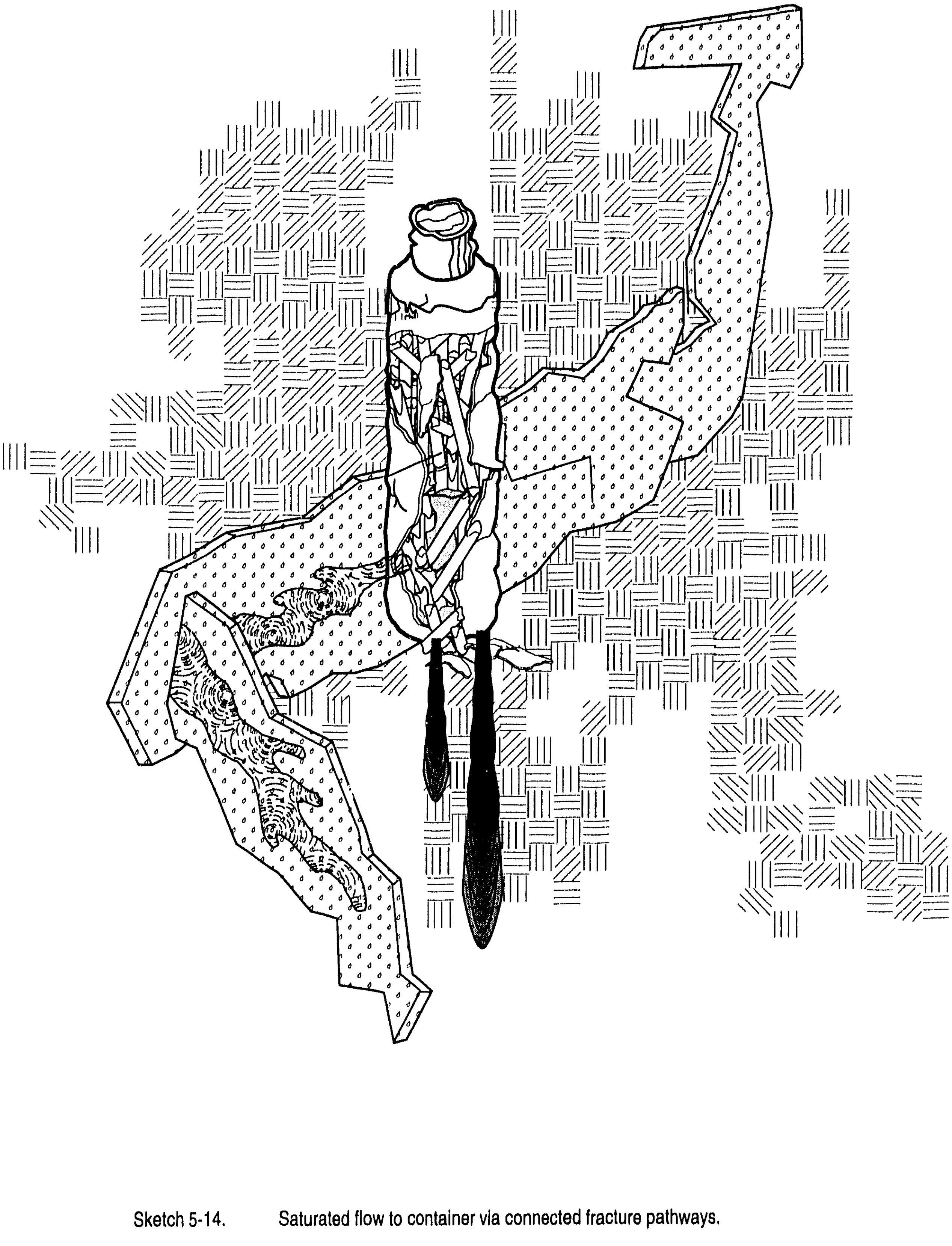
Sketch 5-12. Saturated flow along a macroscopic fracture to a container, producing saturated mobilization and saturated transport along fracture pathways.

as a saturated flow down the fracture pathway and as some leakage to any unsaturated flow field, as it might exist, and proceed to the water table.

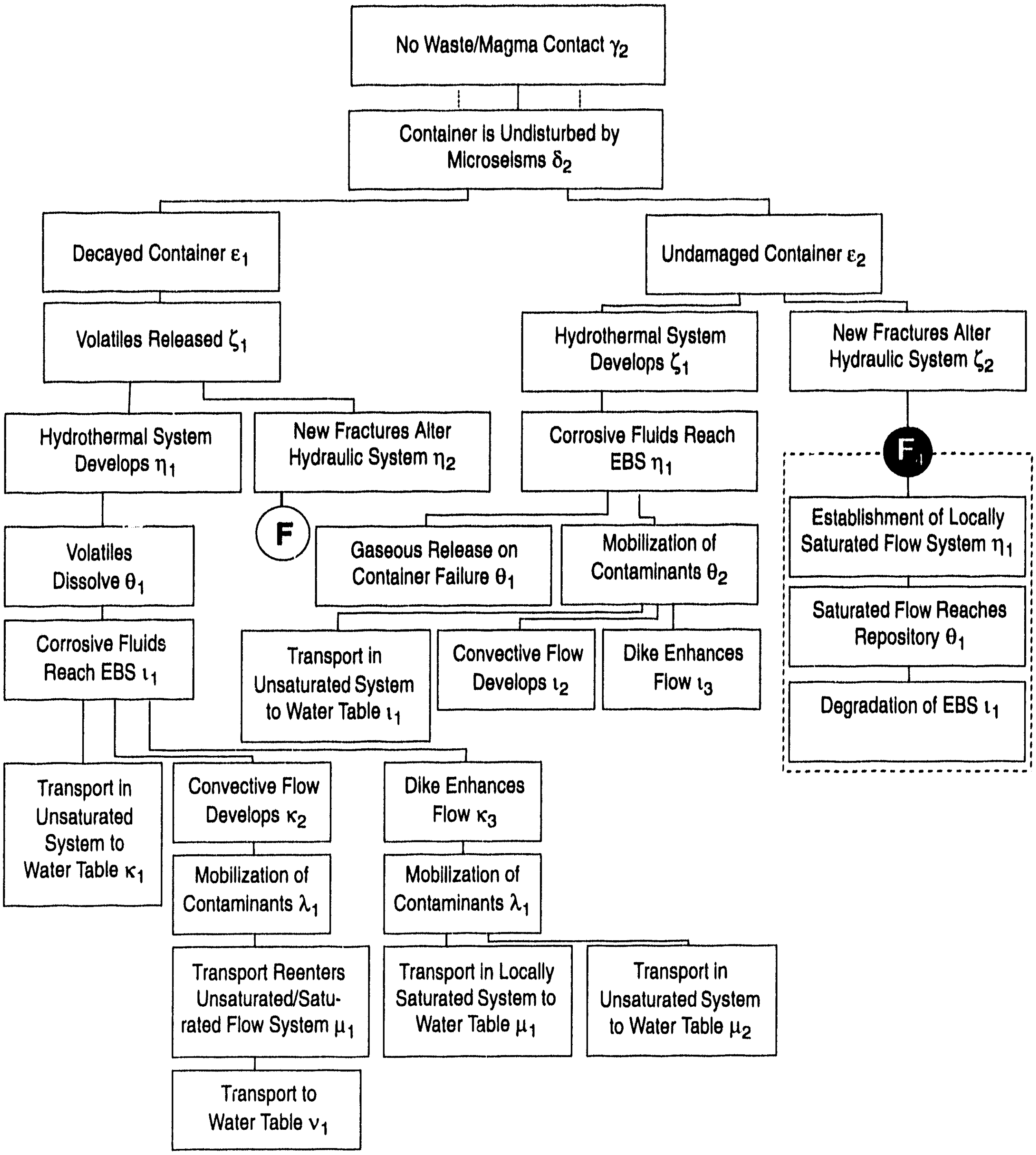
We again reference Delaney et al. (1986) for a possible alteration of country rock where emplacement or cooling of the dike produces a fracture set approximately parallel to the dike and reaching out a few meters from it, i.e. New Fractures Alter Hydraulic System ζ_3, previously described in Ⓕ of Tree Segment 4b. We presume that the hydraulic connectivity of these fractures suffices to alter the local hydraulic flow system. Following 5-6 the new fracture sets are shown in Sketch 5-13, where their interactions with the flow system as altered by the dike are illustrated by reference to the discussion associated with Sketches 4-3, 4-4, and 4-5. The flow may occur via a connected fracture path, as in Sketch 5-14, rather than through fractures continuous in any plane perpendicular to the dike cross section.



Sketch 5-13. New fracture set parallel to the dike caused by insertion of the dike.



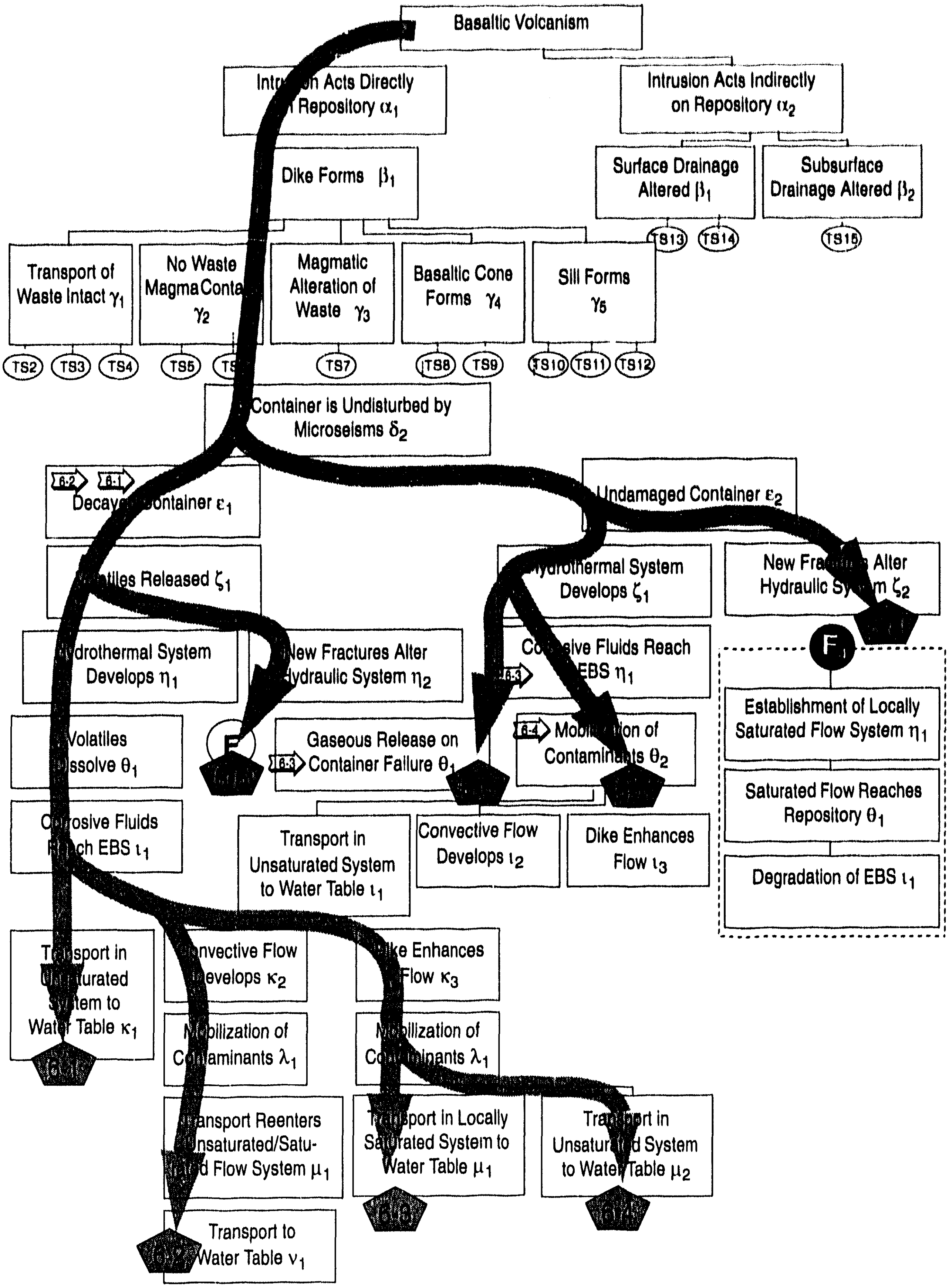
Sketch 5-14. Saturated flow to container via connected fracture pathways.



Tree Segment 6a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, no waste/magma contact γ_2, container is undisturbed by microseisms δ_2.

Container is Undisturbed by Microseisms (TS6)

Tree Segment 6a shows we have an alternative branch to consider under No Waste/Magma Contact γ_2, namely, the case of no damage to the container due to the microseisms (Container is Undisturbed by



Tree Segment 6b. Scenario paths and scenario group paths of tree segment 6a.

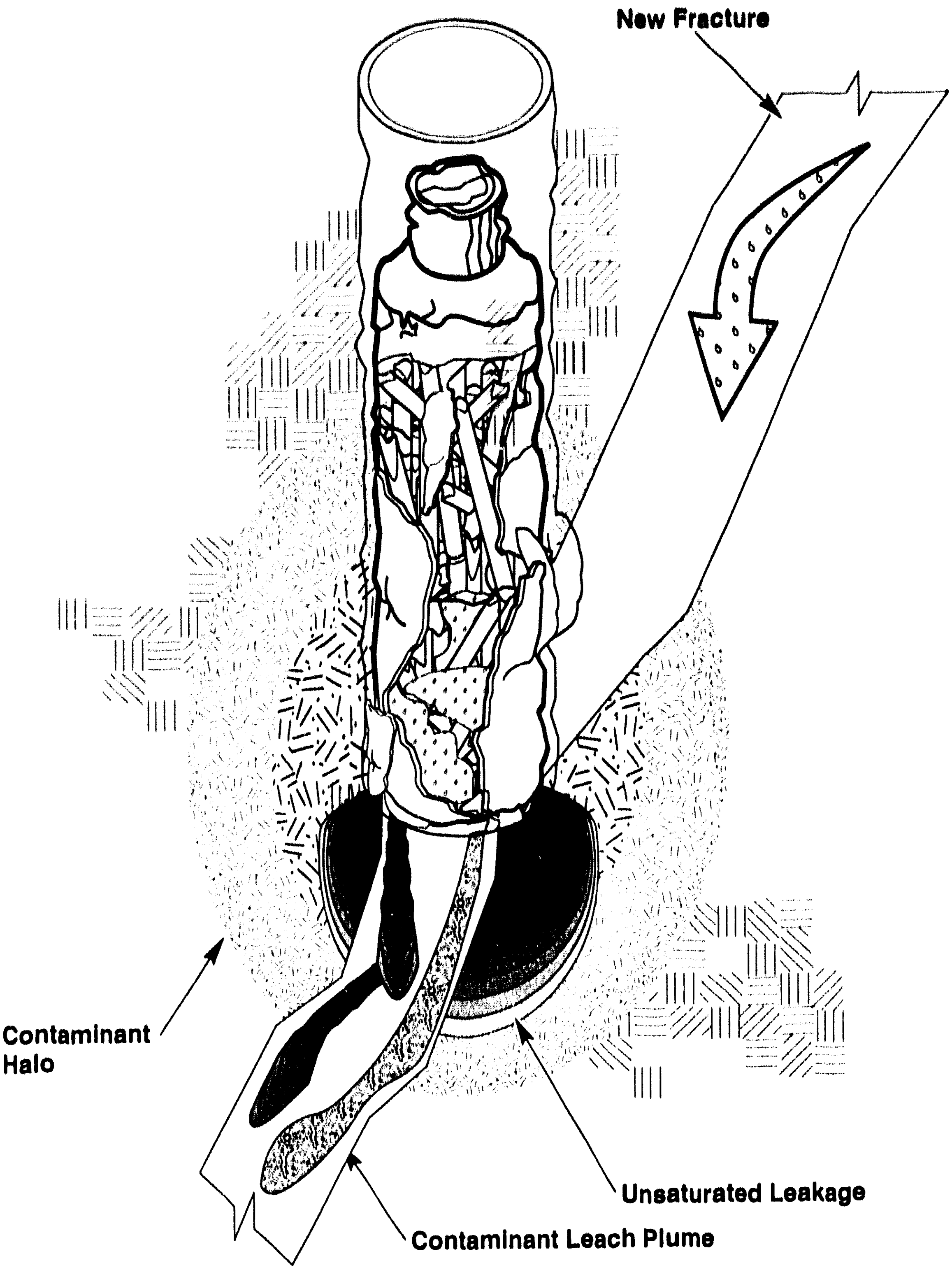
Microseisms δ_2). This is intended to describe two cases: **Decayed Container** ε_1, in which the container is in such a state of decay that any damage from ground motion is irrelevant; and **Undamaged Container** ε_2, in which the container survives without being compromised regardless of the state of the spent fuel debris inside. These distinctions are drawn because heating an intact container mobilizes volatiles from the fuel to eventually condense inside the container on the upper walls, providing an already differentiated source when the container does fail. This plate-out is shown in **Sketches 5-2 and 5-3** in the pristine container. A container that is already decayed, while it releases its volatiles as the container disturbed by microseisms (discussed earlier), has released its gaseous components earlier (e.g., $^{14}CO_2$). For the container that has decayed to the point of seeing no relevant additional damage, the scenarios are those in 6-1 through 6-5 as shown in **Tree Segment 6b**. Some differences from the earlier scenarios for **Container Disturbed by Microseisms** δ_1 are in **Sketches 6-1 and 6-2**. **Sketch 6-1** shows a container in some advanced state of decay. $^{14}CO_2$ has already left the container, so the inventory to be considered is altered. A feature of the history of the decayed container has been added in this section, namely, that it is reasonable for some of the contaminants to already be migrating into the rock surrounding the emplacement hole. Radioisotopes distributed in the rock alter the model of the source by distribution (location) and by chemistry.

Similar arguments obtain for the circumstances involving fractures produced in a zone parallel to the dike as a result of the intrusion and included in the tree as 6-6. The distinction here, apart from the failed container at the start, is again the appearance of contaminants in a plume or halo around the base of the emplacement hole. This "halo" results from mobilization of the radioisotopes from the failed EBS, either unsaturated or saturated mobilization. For entry into a new fracture set in the saturated mode, the behavior could be depicted as in **Sketch 6-1**. There it is presumed that the contaminant halo is interrupted by the new locally saturated flow system and is actively mobilized, as are the contents still in the emplacement hole. Conceivably, radionuclides in the halo are already more mobile and will precede any newly mobilized material down the fracture.

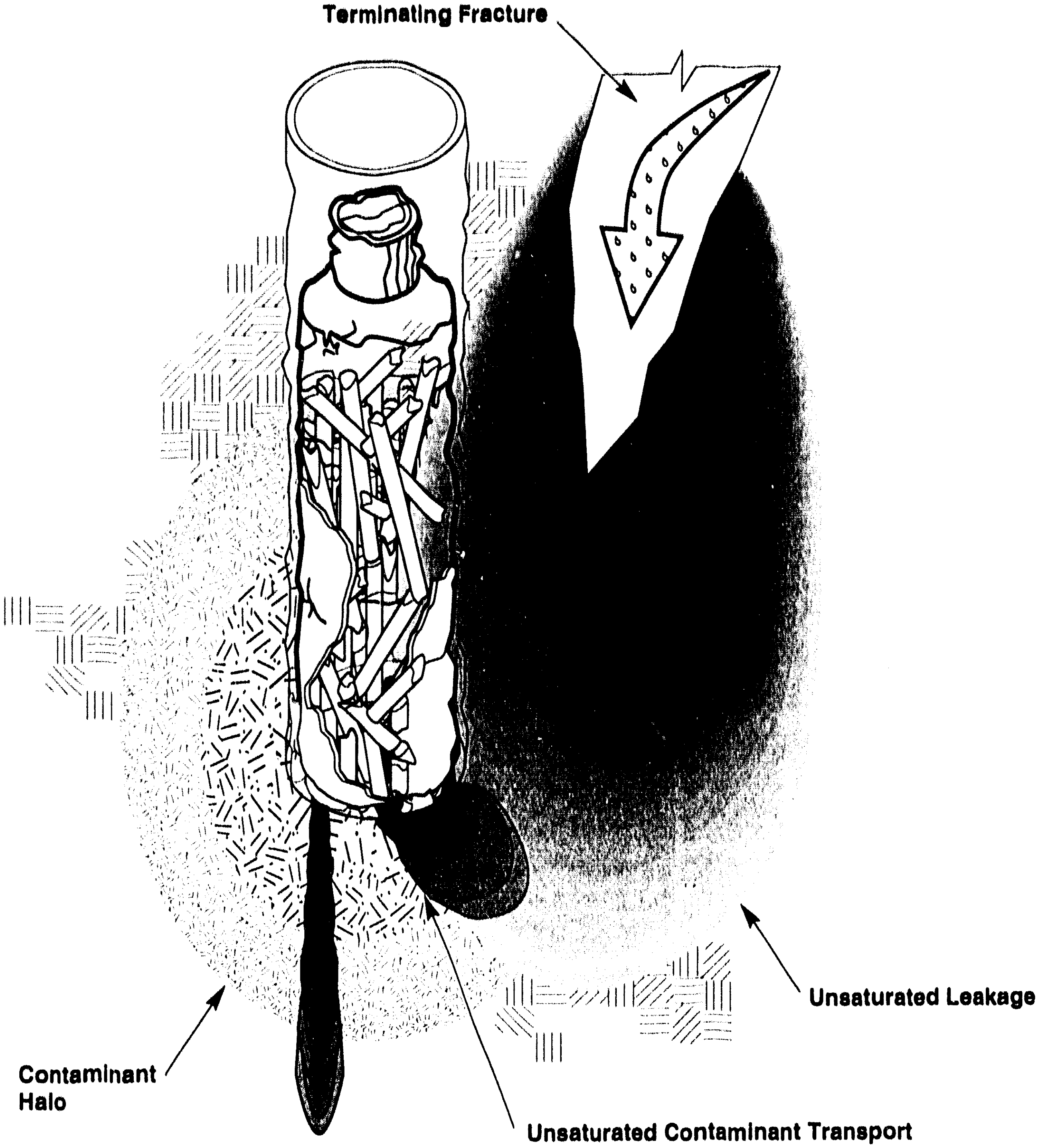
Sketch 6-2 describes the alternate situation of unsaturated leakage (or possibly saturated leakage in the composite model mode) from a blind fracture set over to the decayed container and to the contaminant halo. Radionuclides in the halo are presumably more mobile and are moved first in the enhanced unsaturated or saturated flow system, with additional contaminants mobilized and flowing behind.

At this point we are left with the possibility for the **Undamaged Container** ε_2, the pristine container of **Sketch 2-3**. The thermal load of the dike on the nearby containers could be sufficient to volatilize certain radionuclides. Since they cannot escape, we presume that the volatiles that have exited the spent fuel will recondense elsewhere in the container, most likely in the head, as far from the dike as possible, as in **Sketches 5-2 and 5-3**. Similarly there will be some readjustment within the intact fuel rods. Whether either redistribution has any significant impact on the source term or its mobilization remains to be seen. We assume for this discussion that it does.

A possibility is the development of an active hydrothermal flow system driven by the dike and accompanied by magmatic volatiles given off by the dike (e.g., SO_2, H_2S, CO_2, H_2O, HF). The net result is a corrosive fluid that reaches containers. No release occurs unless the container is breached by this combination of hostile constituents. Note that if the repository is itself still quite hot, then the nature of the corrosive fluid may change (e.g., relative proportions of H_2O and sulfides). A compromised container is shown in **Sketch 6-3**, where the

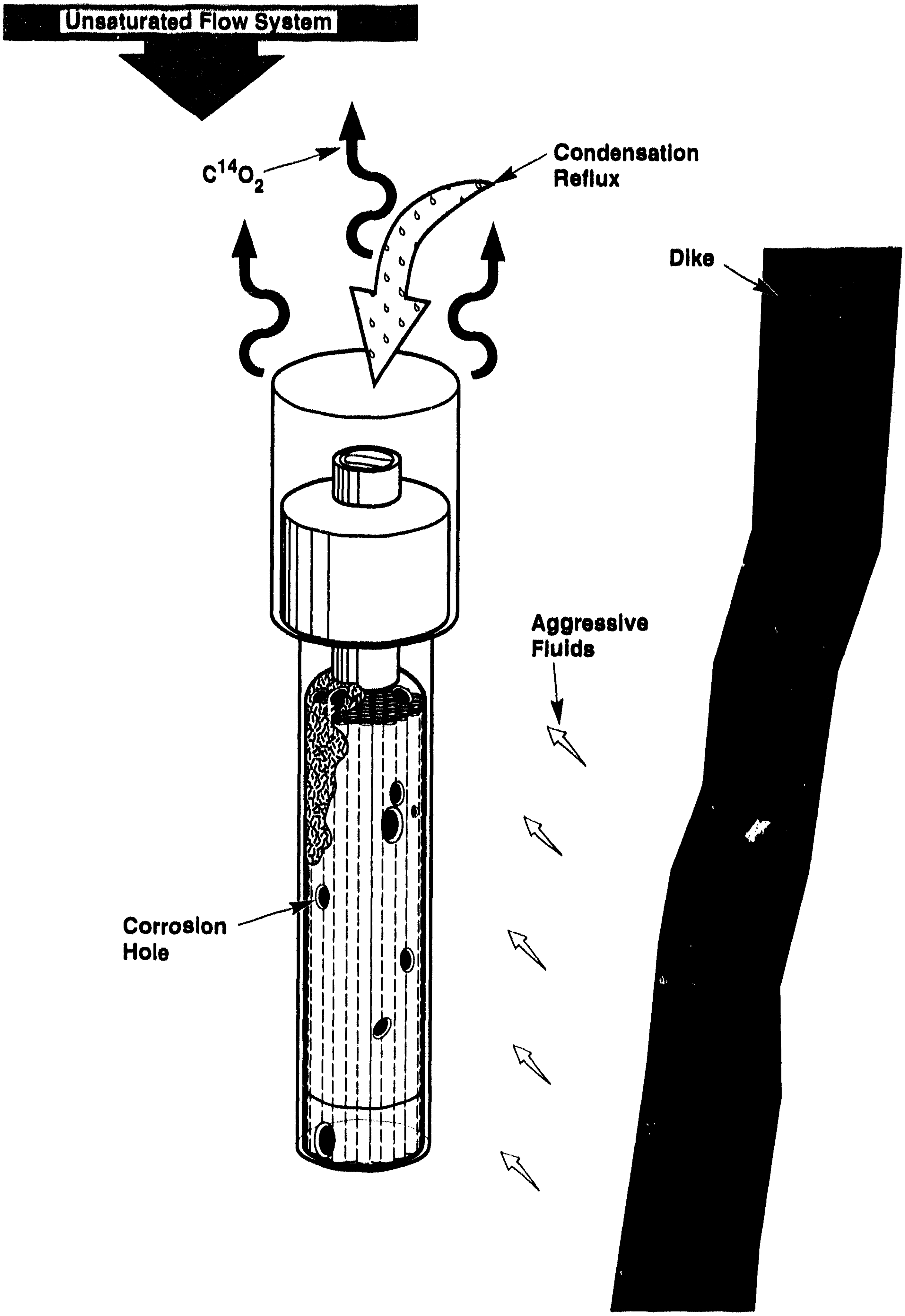


Sketch 6-1. A contaminant halo of mobile radionuclides previously leached into the surrounding rock increases contaminants available for saturated transport in the new fracture.

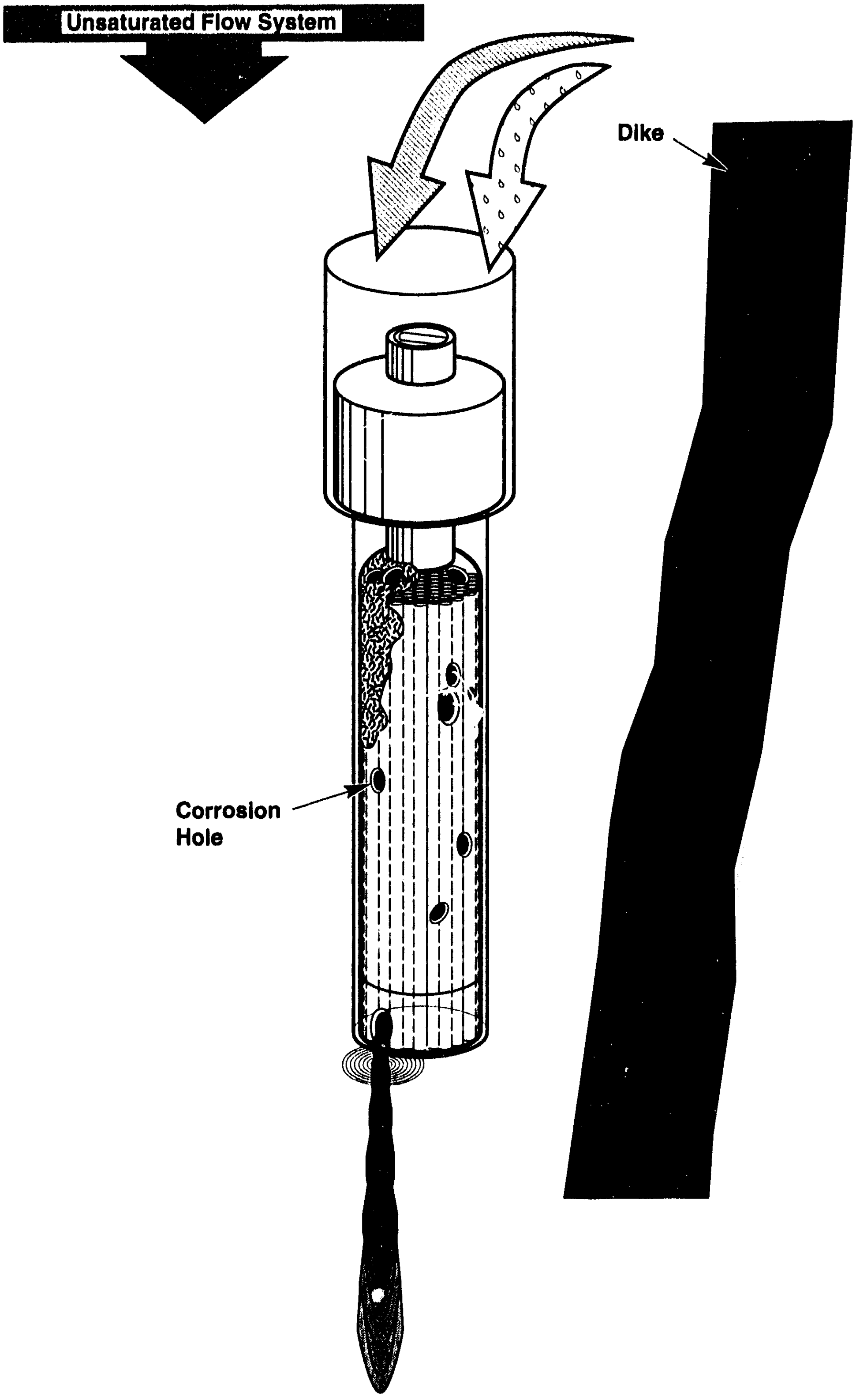


Sketch 6-2. A contaminant halo of mobile radionuclides previously leached into the surrounding rock increases contaminants available for unsaturated transport.

sudden release of radioactive volatiles is indicated schematically. Presumably, there has been no release until corrosion holes appear in the container, which because of the elevated temperature, is further pressurized. We thus have the gaseous release scenario of 6-6. This discussion leaves us with the extraction of contaminants of the now compromised container and their entry into the flow system, similar to the earlier discussion for damaged containers. In effect the container is now a decaying container as shown in Sketch 6-4, except for mechanical damage to the fuel rods, so the scenarios obtained earlier apply with a few obvious corrections. New scenario path groups, similar to those developed earlier, are 6-7 and 6-8. This list concludes the discussion of intrusion of No Waste/Magma Contact γ_2.

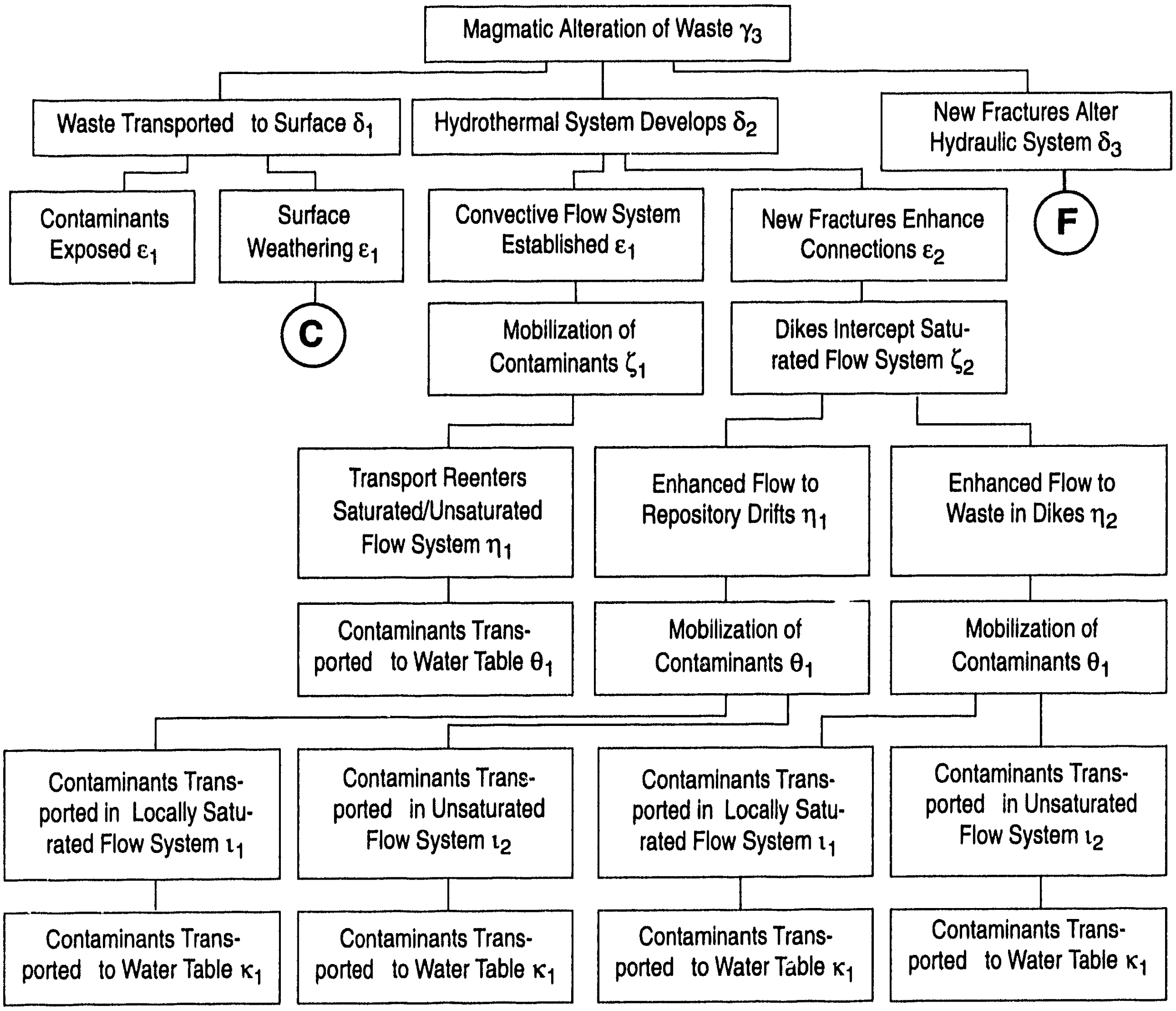


Sketch 6-3. Aggressive fluids from dike breach container; radioactive volatiles escape.



Sketch 6-4. Multiphase effects with the dike as a thermal source.

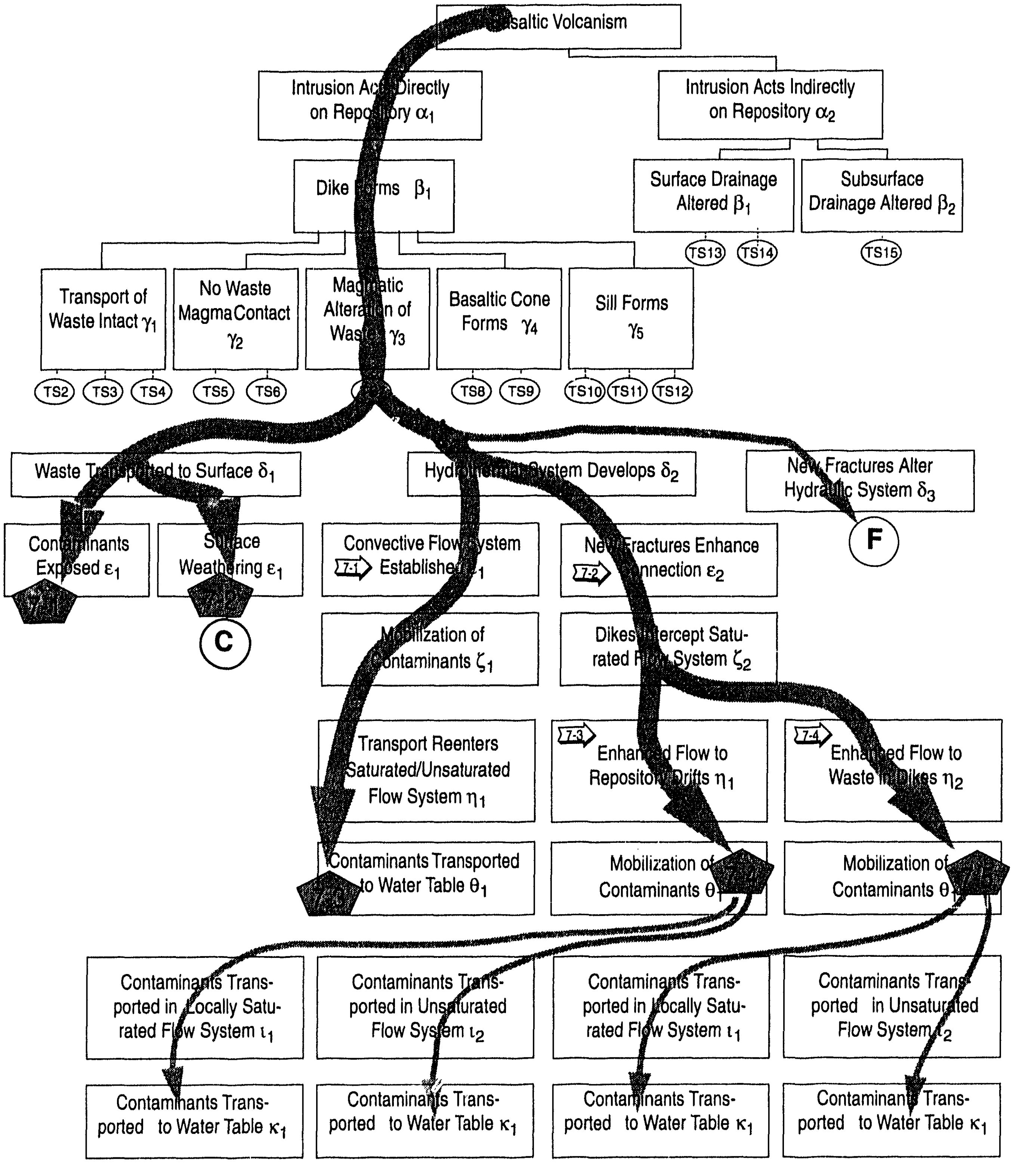
Magmatic Alteration of Waste ($\alpha_1, \beta_1, \gamma_3$)



Tree Segment 7a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, magmatic alteration of waste γ_3.

Magmatic Alteration of Waste (TS7)

(TS7) addresses physicochemical alteration of the waste (Magmatic Alteration of Waste γ_3). This is the next discussed possibility for a dike acting directly on the potential repository. In this case the intrusion contacts waste and alters it in some chemical sense while transporting it. Waste that is entrained but not altered was discussed in (TS4). This is taken to mean more profound chemical interaction of waste and magma than encapsulation and transport; because such interaction might alter the form of the waste to enhance its solubility in water. Spent fuel is relatively refractory; magma temperatures are on the order of 1100 °C. Basaltic magma is probably too close to saturation in iron for effective dissolution of containers and chemical diffusion of contaminants in cooling magma is expected to be slow. Multiphase eutectic mixtures of magma and these contaminants are not known or known to have been investigated. However, we are compelled to consider all these



Tree Segment 7b. Scenario paths and scenario group paths of tree segment 7a.

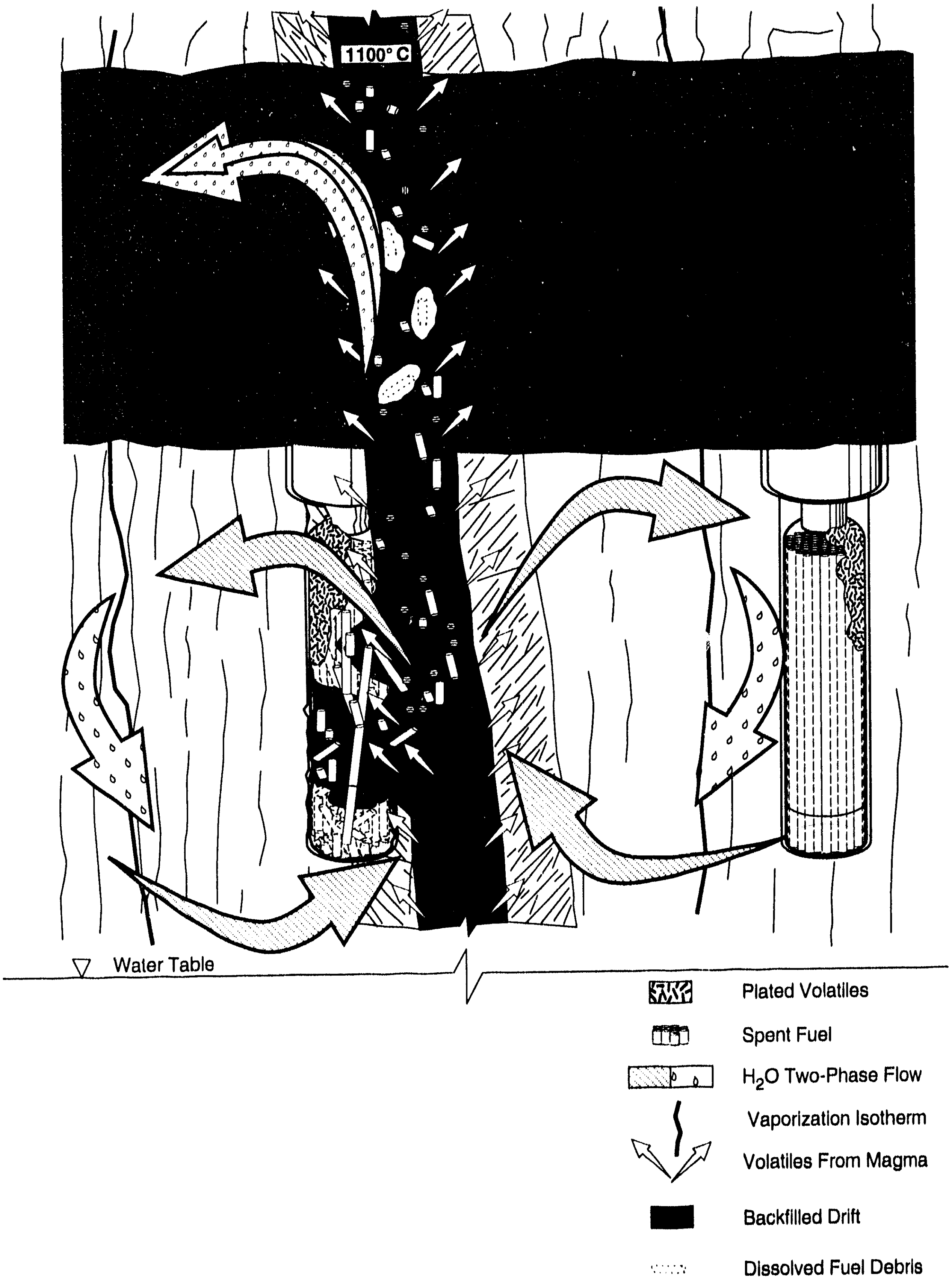
possibilities, particularly as dikes are known with substantial radioactive signatures. In addition, waste from reprocessing is currently expected to be in glassified form. Glass waste softens and melts below magma temperatures, so contaminants from such waste could react with the magma or dissolve in it. The source term for mobilization must be altered accordingly. While we will continue with the discussion as if the waste were spent fuel, the reader is asked to recall that other waste forms are possible and that those forms affect the source term and the mobilization of contaminants.

We have encountered the events and processes of 7-1 and 7-2 in the left branch Waste Transported to the Surface δ_1 in an earlier discussion describing 2-1 through 2-5. Those scenarios included direct transport to the surface with direct exposure and surface weathering. Except for radionuclide distribution in the extrusion, the observations are the same.

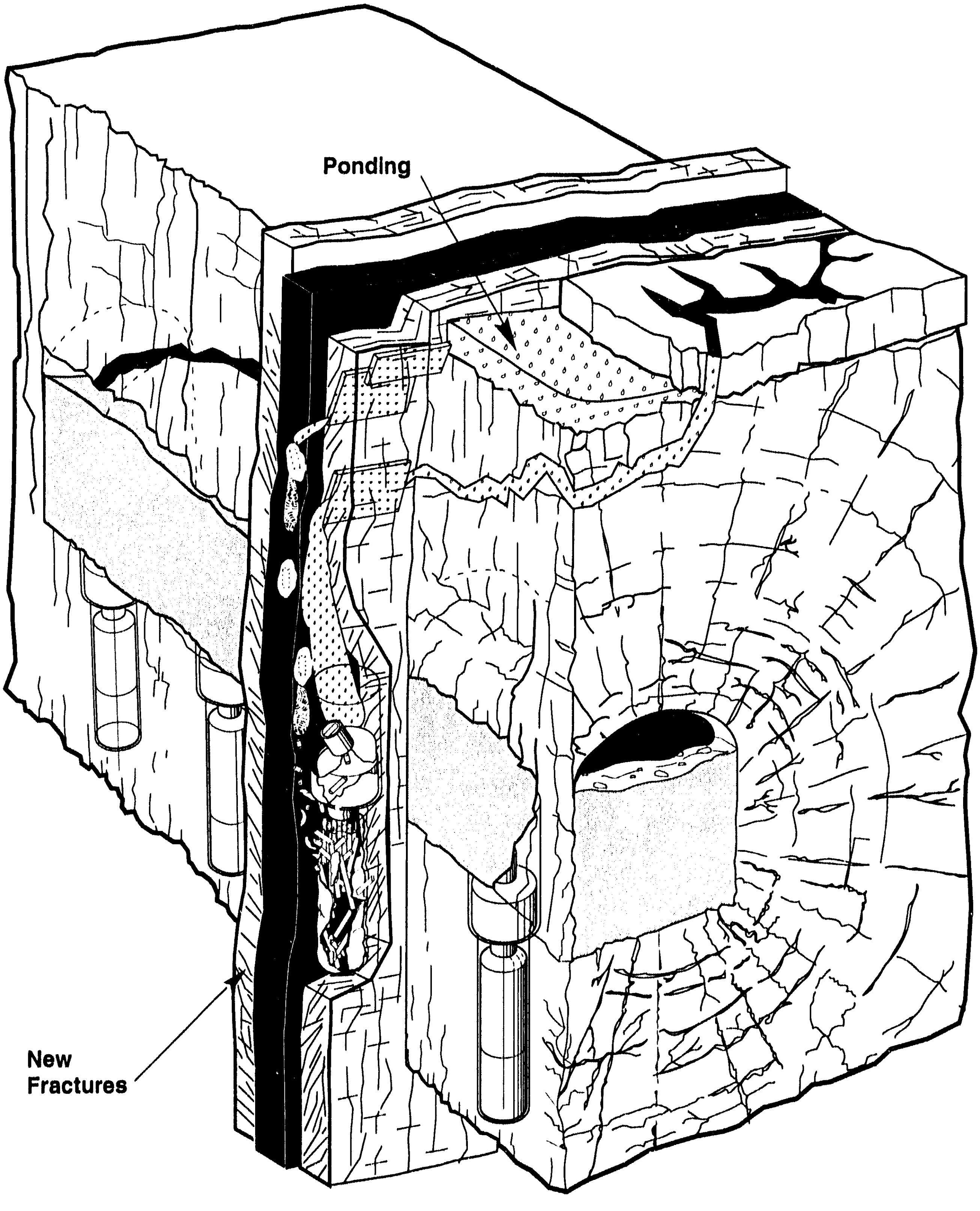
Likewise 7-3, the Convective Flow System Established ε_1 branch of Hydrothermal System Develops δ_2, is as discussed in (TS3). In (TS7) we presume that pockets of dissolved spent fuel persist, and that flow in the dike is not well-mixed (Carrigan and Eichelberger, 1990; Valentine, 1989). The general movement is up the dike with the magma. No circulation of water to mobilized waste is possible until the dike has cooled and solidified. It is conceivable that the dike could provide a transient single-phase convective flow system that mobilizes contaminants out of the dike into the normal flow system, which is re-establishing itself. These processes are contained in Sketch 7-1. Once these contaminants have entered the flow system, they are presumably transportable to the water table.

It is unclear how the now familiar possible fracture sets parallel to the dike of Sketch 7-2 would allow enhanced access to mobilized waste in the structure of the dike except if the fractures add to the pathways in formation of a hydrothermal system; accordingly we have New Fractures Enhance Connections ε_2. We have noted the possibility that the dike intercepts or forces the formation of a saturated flow system. This is shown in Sketch 7-2, where the dike blocks a locally saturated flow system and thus forces ponding. This feeds flow down the dike and down fractures caused by the dike and finally causes fracture flow. Tree Segment 7, under Dike Intercepts Saturated Flow System ζ_2, distinguishes between flow directed to the potential repository and flow down the dike. In both cases the targets of the flow for mobilization are the dissolved pockets of contaminants. In the former case, 7-4, the contaminants have been transported laterally into the voids in the backfilled drift. They see the backfill below and possibly around them; that is, they are in contact with a classical porous medium while encased in a solidified, tabular mass of magma. This situation is shown in Sketch 7-3. The mode of further transport, saturated or unsaturated, depends on the characteristics of the Topopah Springs and Calico Hills immediately below the drifts as well as on the nature of the stress-altered region around the drifts and containers. With respect to the second case, Enhanced Flow to Waste in Dikes η_2, 7-5, flow down and through the dike is necessary to reach the dissolved waste. Sketch 7-2 shows how saturated flow could be made available by the dike. We expect that the dike could itself be fairly well fractured in the course of cooling. The saturated flow caused by blockage of lateral, unsaturated flow or of locally saturated flow is directed down the dike, mobilizing contaminants where they are accessible, as shown in Sketch 7-4. The dike and its fractures are then the conduit system for transport to the water table.

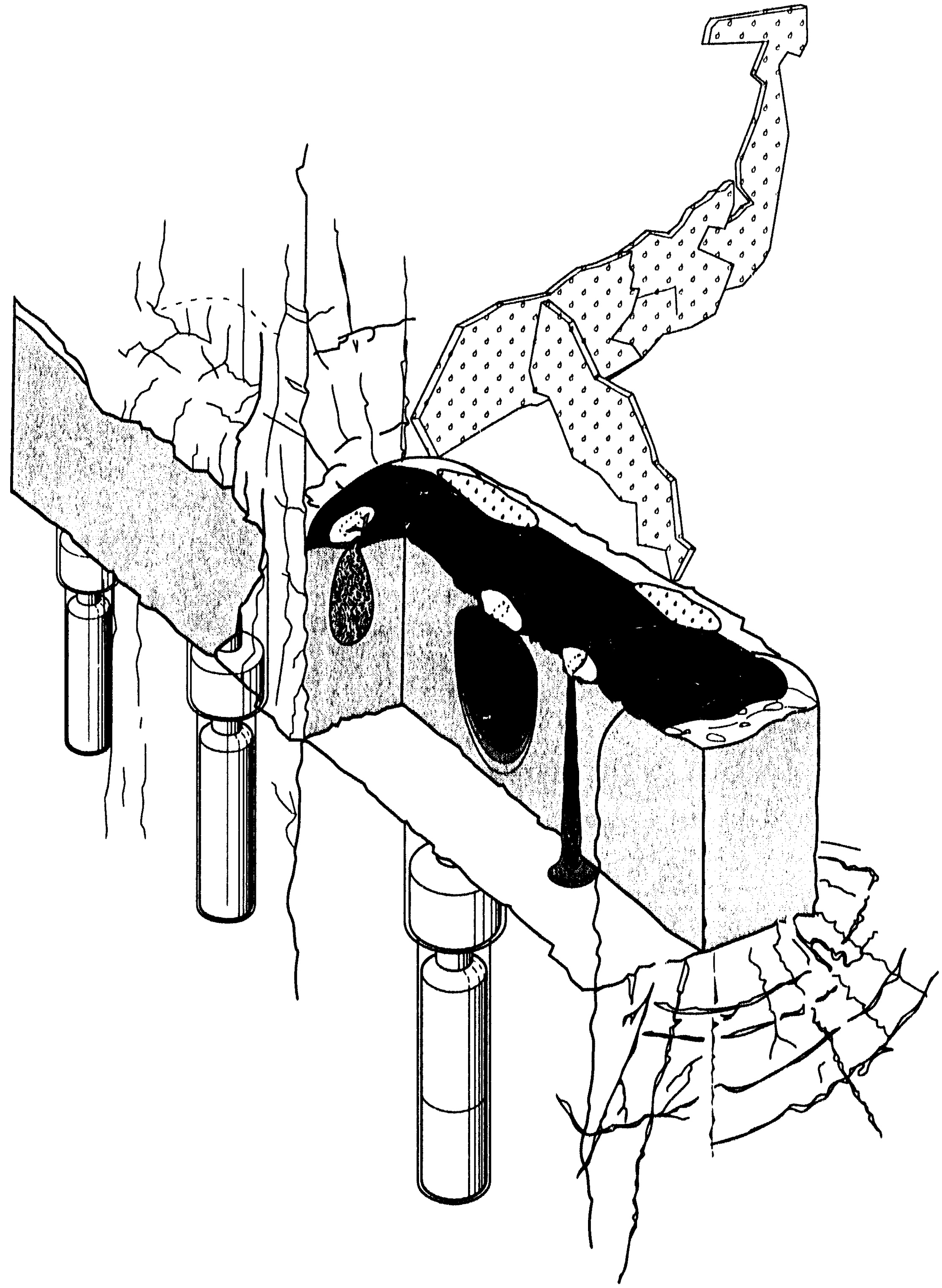
This completes the discussion of scenarios involving Magmatic Alteration of Waste γ_3.



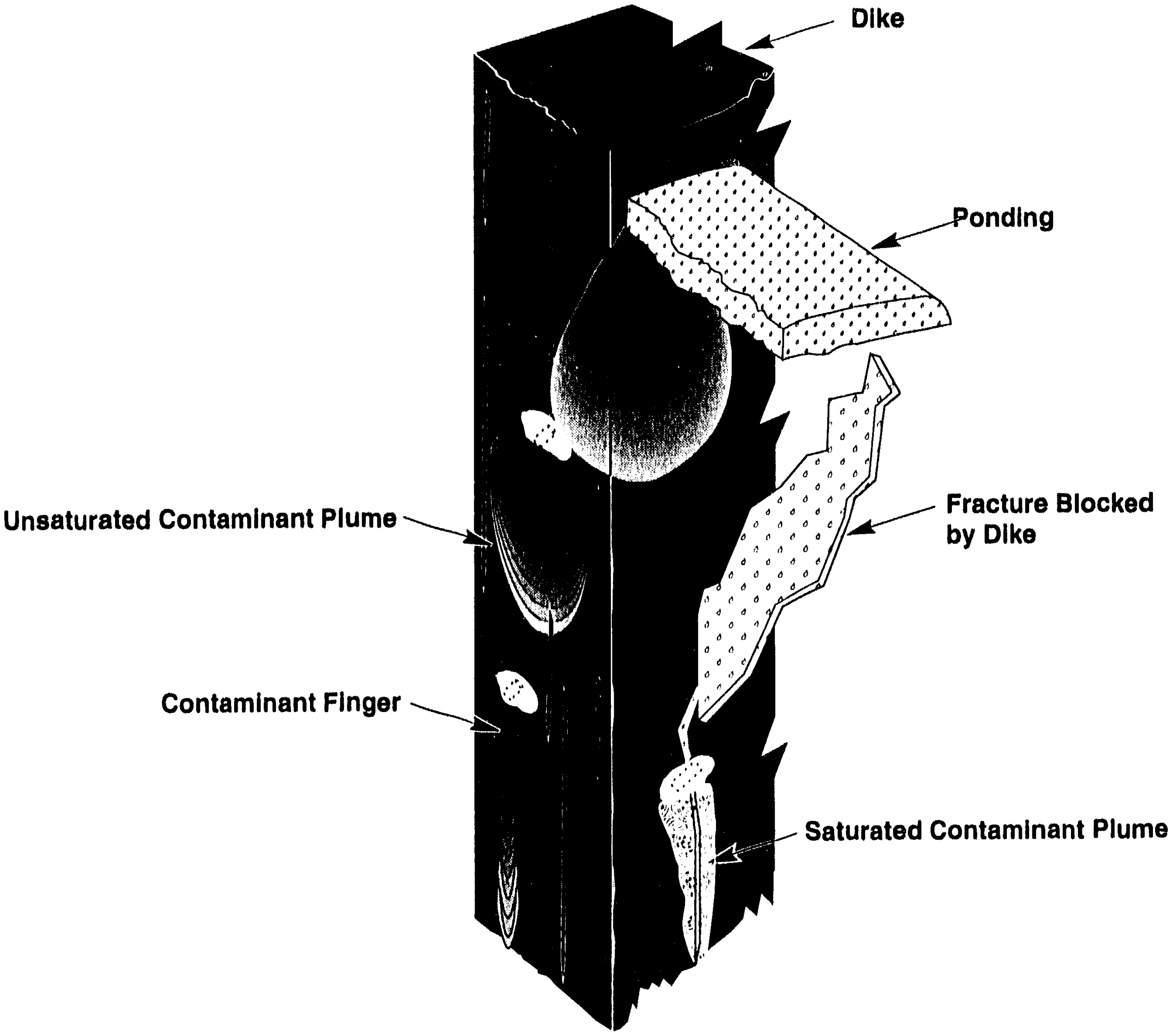
Sketch 7-1. Hydrothermal system with magmatic alteration of waste.



Sketch 7-2. New fractures enhance flow to altered waste in the dike and to a container.

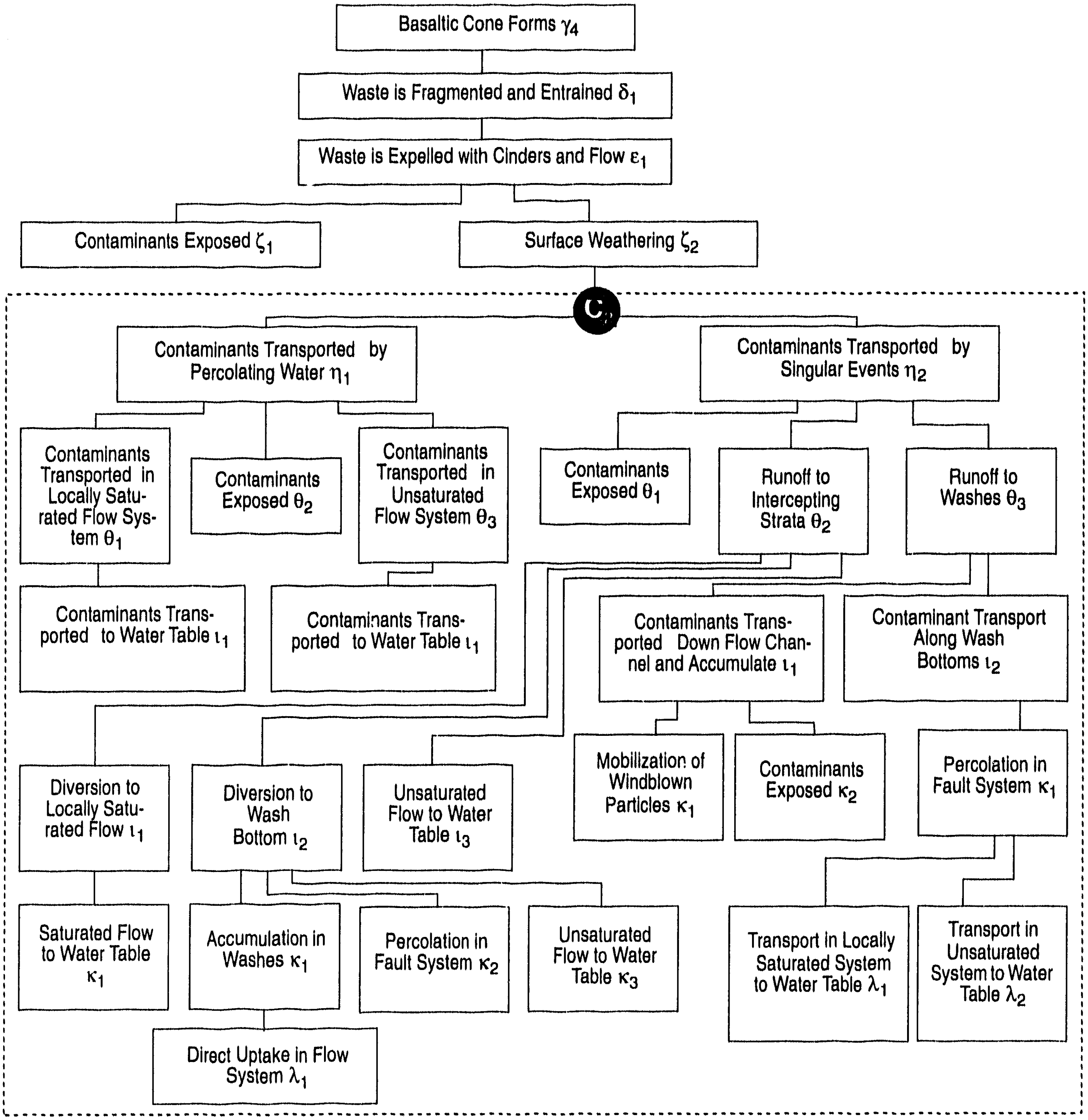


Sketch 7-3. Mobilization into backfill.



Sketch 7-4. Mobilization of altered contaminants in a fractured dike.

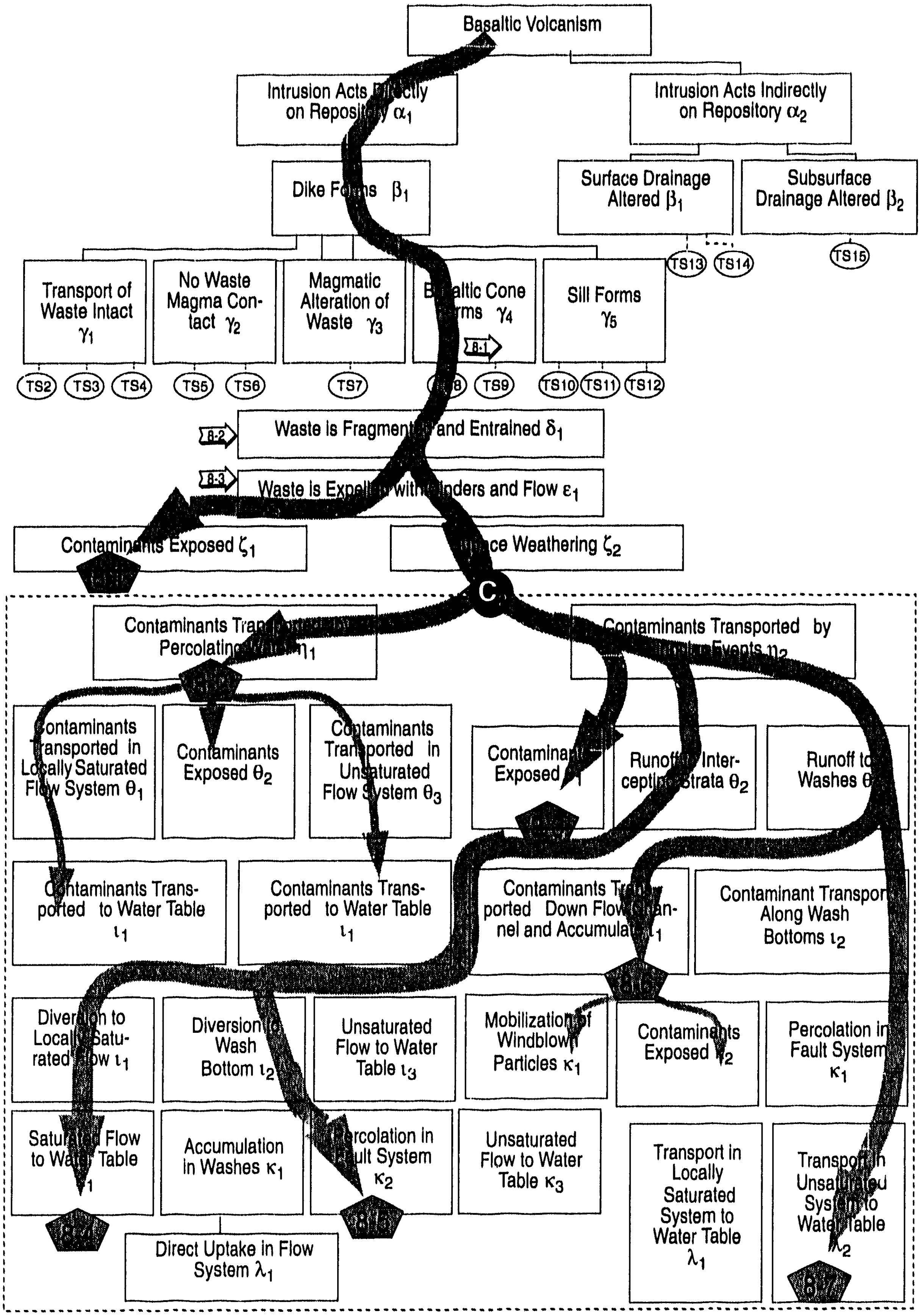
Basaltic Cone Forms ($\alpha_1, \beta_1, \gamma_4$)



Tree Segment 8a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, basaltic cone forms γ_4, waste is fragmented and entrained δ_1.

Waste is Fragmented and Entrained (TS8)

Perhaps the most dramatic evidence of basaltic volcanism, as shown in Sketches 1-1 and 8-1, is the appearance of a cinder cone. There are a number of such cones south and west of Yucca



Tree Segment 8b. Scenario paths and scenario group paths of tree segment 8a.

Sketch 8-1. Basaltic cone forms.

Mountain; these have been studied in some detail (Wells et al., 1990). We will choose the typical cone of our paradigm from this set and presume a cone will form.

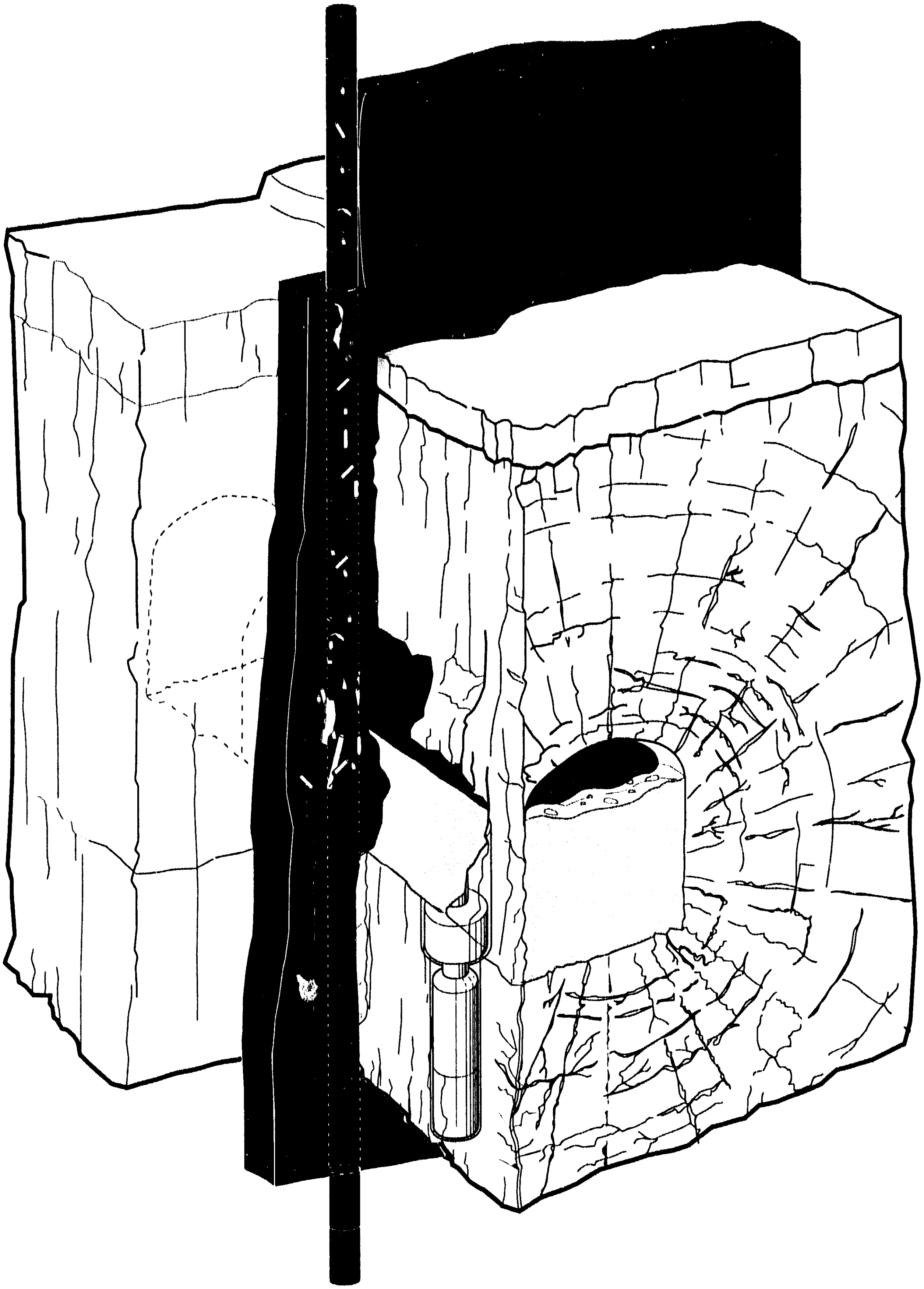
These cones appear to be polycyclic eruptions, with the last eruption at Lathrop Wells cone perhaps 25 thousand years before present (Wells et al., 1990). There seems to be a phreatomagmatic component to the eruptions, followed by strombolian ash and scoria contributions. The observations of polycyclicity and initial phreato-magmatic eruptions suggest return of the water table to roughly its pre-eruption regional level between events. Phreatomagmatic eruptions would be expected to produce a different size distribution of particulates and fines of constituents. We will presume that every eruption begins as a phreatomagmatic event and proceeds into a strombolian event.

All of the scenarios developed here involve rapid removal of waste and its ejection in particulate form or in a lava at the surface, where direct exposure or surface weathering produces an immediate or an eventual biological impact.

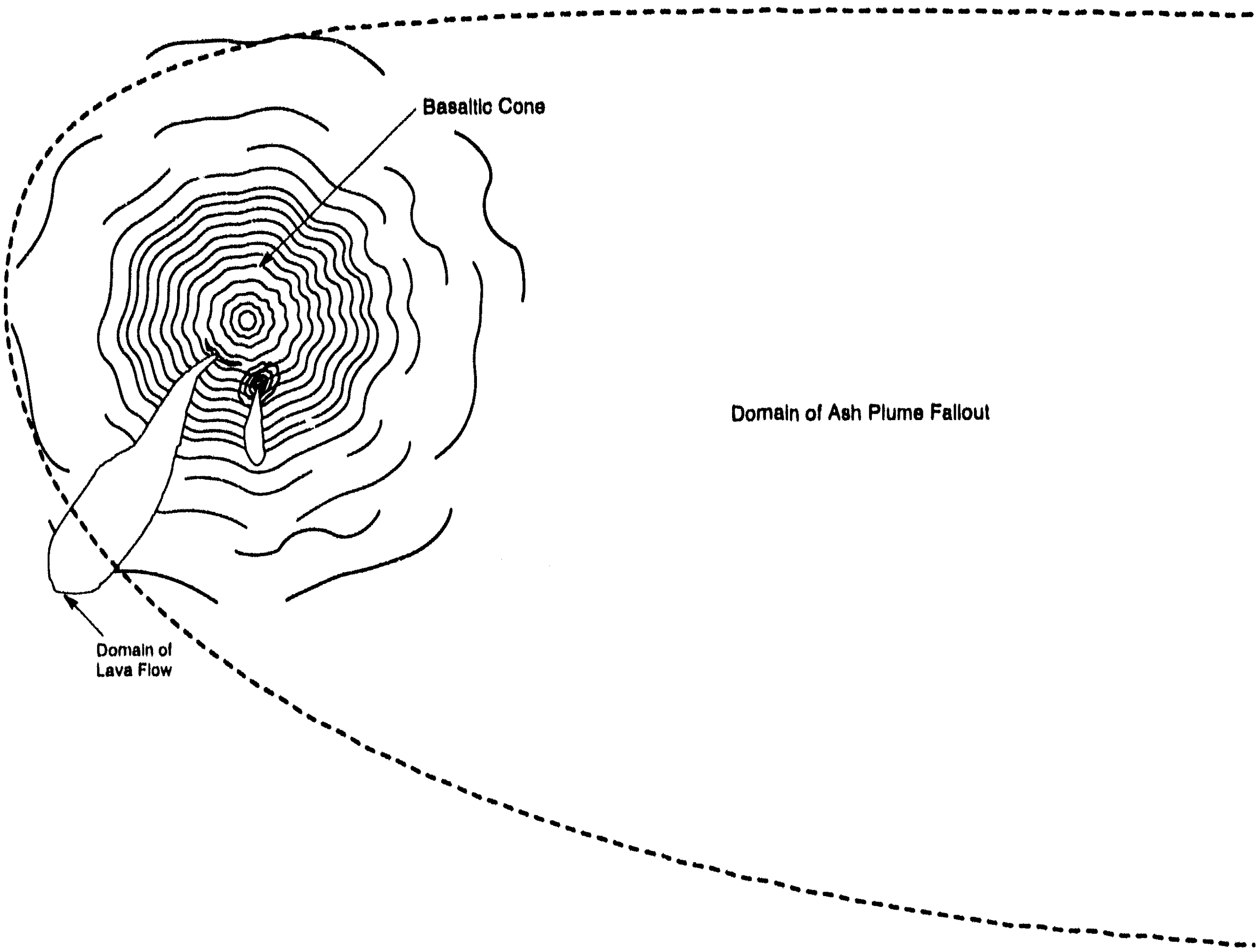
The basic issue is how material being ejected to form the cinder cone interacts with the potential repository. This interaction defines the number of containers at risk. In effect we are asking about the plumbing of the cinder cone and the initial and repetitive use of that plumbing. The problem with the plumbing is illustrated in Sketch 8-2. Generally the vent size is small; one to two meters would be a typical diameter. This means that unless there has been horizontal flow in the dike during emplacement (which is possible), only one container can be in the vent. Unless the vent plumbing wanders on each reactivation cycle, only nearest neighbors seem to be at any risk. We lack information on how flow in the dike focuses to a single vent, and understanding of the deeper processes in the dike contributing to the dynamics of flow to vents. Containers are currently expected to be emplaced within a drift perhaps 5 meters apart (pitch) with drifts separated by 30-40 meters, if the SCP-CDR reference configuration (SNL, 1987) is the emplacement mode chosen. Erosion by repeated eruptions is not expected to cause rapid growth of the vent, as evidence suggests little if any growth once the conduit is established. Even if erosion does occur, unless there is a mechanism for the conduit wandering about, or creation of alternate conduits, only single containers in a row appear to be at risk, as suggested by Sketch 8-2. Note however, the specifics of this interaction may change for alternative container materials, waste forms, and particularly alternative modes of emplacement. These specifics are to be addressed in the detailed modeling of scenarios; the overall structure of Tree Segment 8 may remain unchanged. The exact behavior of the plumbing system supplying these cinder cones has not yet been resolved.

The process of entrainment of fragmented fuel can also be seen in Sketch 8-2. We have no data on how fuel would be mechanically broken by such a magmatic flow. Reasonable analogy exists, however, in plucking of lithic fragments from depths of rock similar to those of the potential repository (Crowe et al., 1983). One should also observe that spent fuel, in particular high-burnup spent fuel, might be expected to have the consistency of lumpy sand. There is an additional complication for the initial flow up the conduit; flow passes through the stress-altered region around the drift. Voids in the drift could be expected to interact with the magma flow system, perhaps relieving the driving pressure and reducing vesiculation. This is a matter to be modeled.

So far we have discussed what amounts to the source term for the surface deposition of all the ejecta. A plan view of the surface deposition of the volcano in Sketch 8-1 is drawn in Sketch 8-3. Since the paradigm for the cinder cone and associated ejecta (including flows) is the



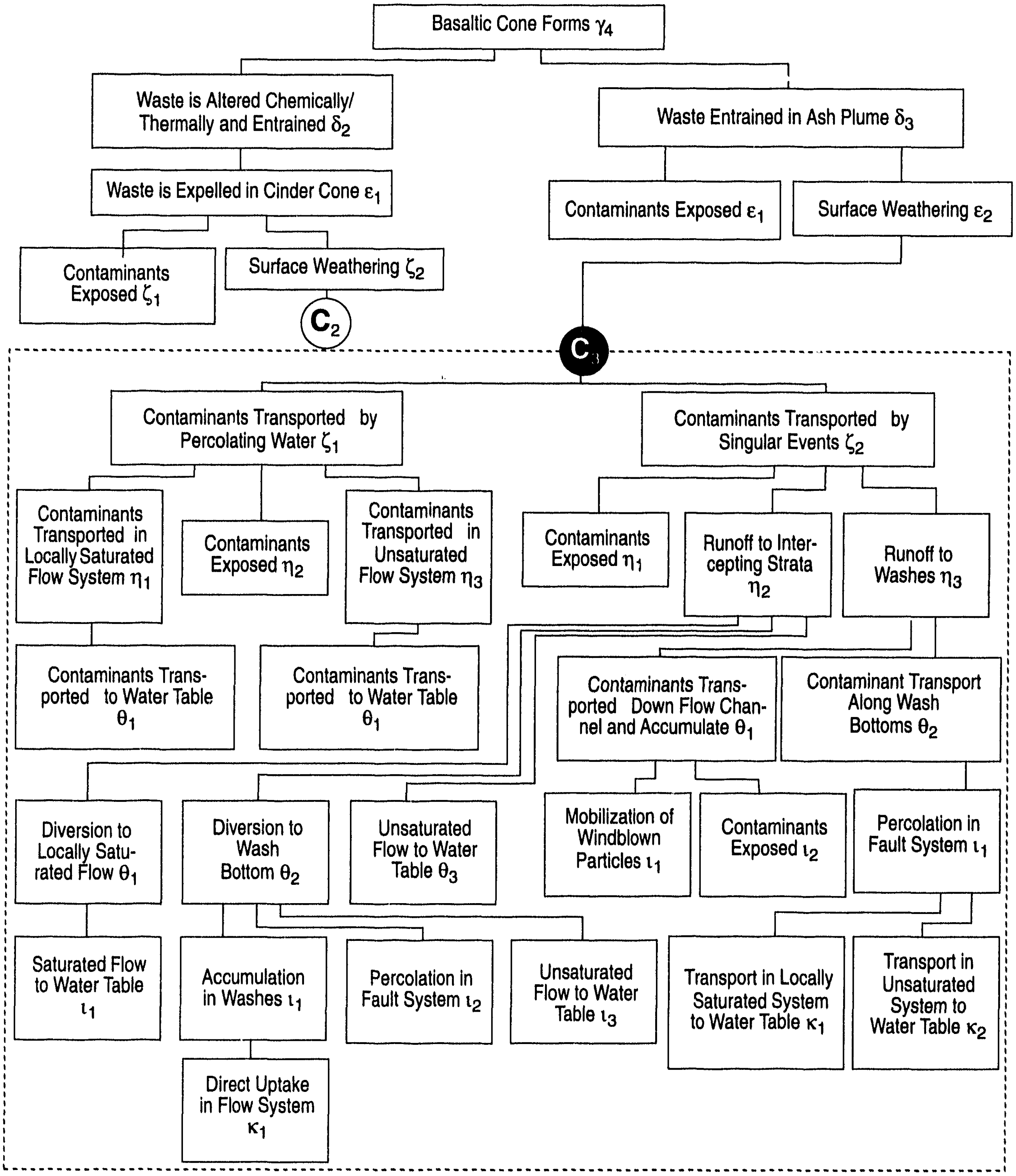
Sketch 8-2. Vent of cinder cone through the potential repository intercepts a waste container.



Sketch 8-3. Domain of ash fall and domain of lava flow in relation to the volcanic cone.

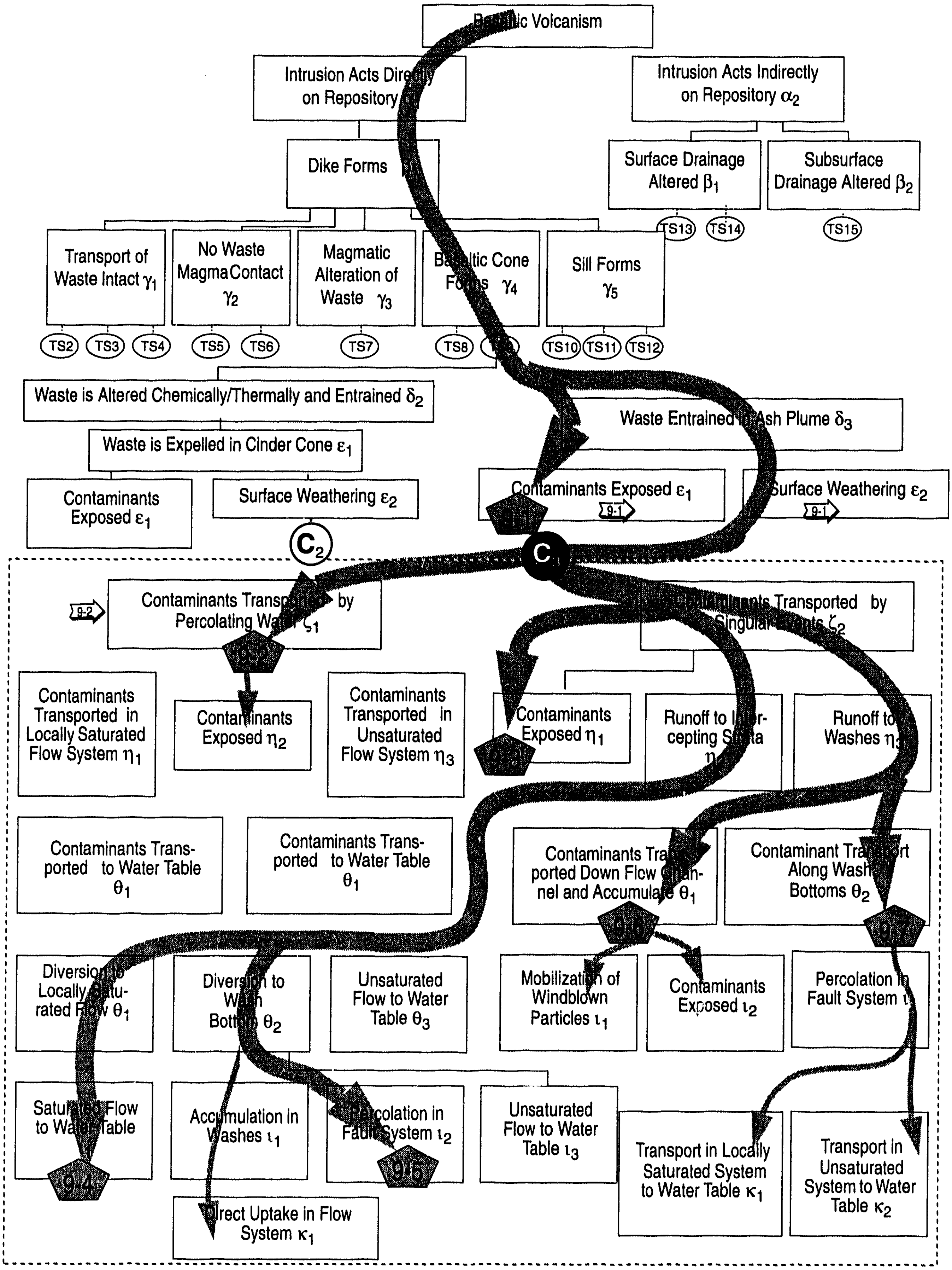
Lathrop Wells cone, numbers are available for the dimensions in the plan view (Wells et al., 1990). The extent of the ash fall is somewhat more problematic; however, the interested modeler can get guidance from Link et al., 1982, and a number of references on plumes and particulate deposition given there. Sketch 8-3 shows the region of risk for direct exposure of 8-1, and establishes the circumstances of the depositions for scenarios involving surface weathering. In this respect we are referring to surface weathering, which we previously discussed in 🅒 of TS2 and refer to now for the paths 8-2 through 8-7. The processes are the same as those for the discussion of a lava flow being eroded and infiltrated, except the amount of waste brought to the surface, its distribution, and the geometry of the surface being weathered are different for a cinder cone.

It is possible that contaminants accumulate in the wash at the bedrock/alluvium interface and are gradually mobilized in the unsaturated flow system, eventually to be transported to the water table. Even though this possibility exits, release of radionuclides from this path involves transport over a greater distance to the water table than for material in the potential repository; so, unless chemical studies suggest a reason for greatly enhanced mobility of the waste that has passed through the volcano, we will consider resulting releases insignificant.



Tree Segment 9a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, basaltic cone forms γ_4, waste entrained in ash plume δ_3.

Waste Entrained in Ash Plume (TS9)



Tree Segment 9b. Scenario paths and scenario group paths of tree segment 9a.

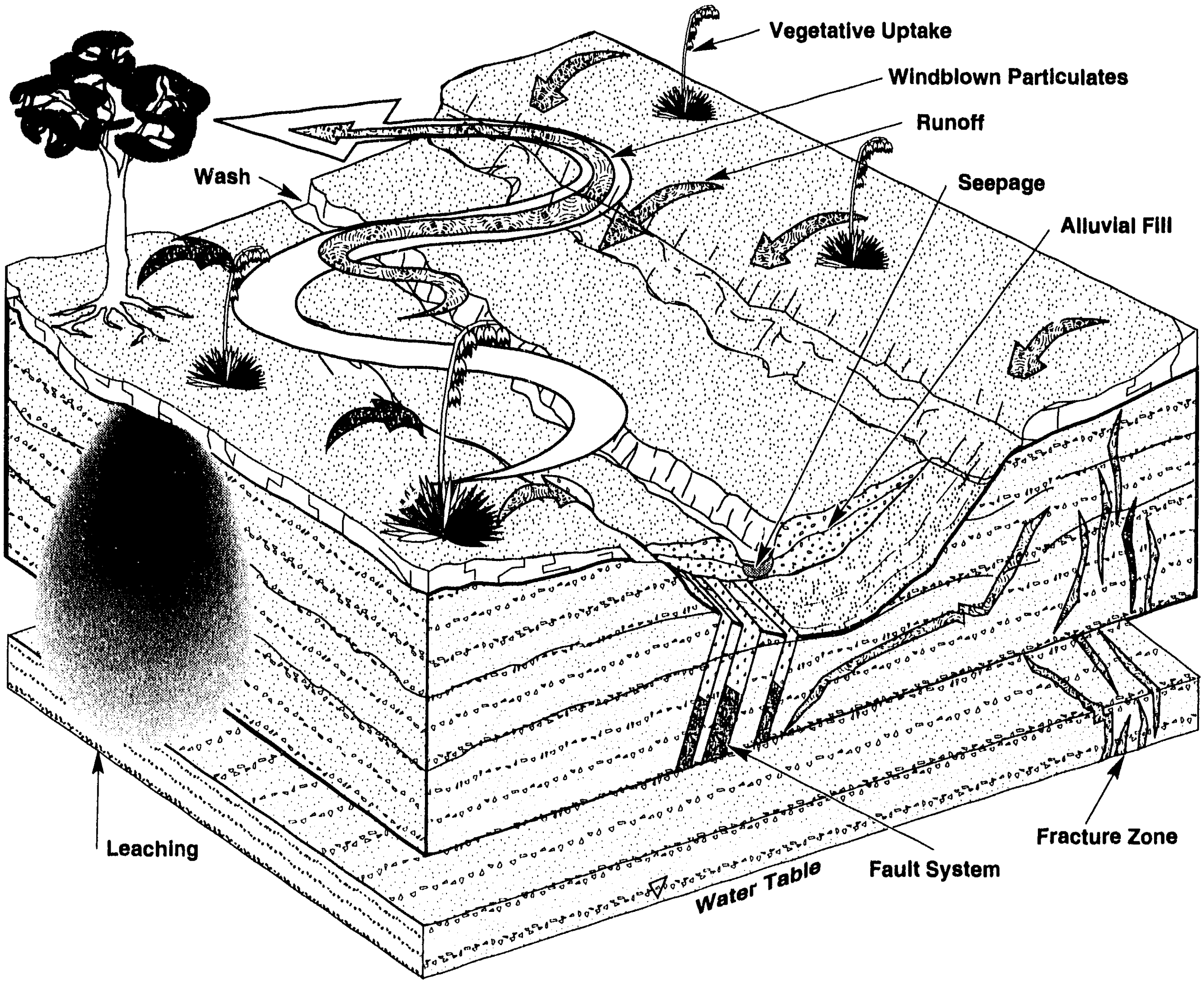
Referring now to Tree Segment 9, we see the second branch below Basaltic Cone Forms γ_4, Waste is Altered Chemically / Thermally and Entrained δ_2, which considers waste chemically and thermally altered before being belched out onto the cinder cone. The difference between this branch describing chemical/thermal alteration of the contaminants and the just discussed branch in Tree Segment 8 describing mechanical fragmentation and entrainment will appear in the specific modeling of the chemistry involved in the leaching and mobilization processes. All descriptive figures, at the level of detail we are specifying so far, remain unchanged. Accordingly we will simply refer to the preceding scenario and scenario group paths of (TS8) and the weathering processes detailed in (TS2), and remind the modeler and reader of the implicit details that are required.

This leaves us with one remaining topic for the formation of the cinder cone and ejecta, namely Waste Entrained in Ash Plume δ_3, the branch containing the formation and deposition of the ash cloud. The ash cloud is distinguished from the other ejecta by the sizes of particulates and by the area of deposition. Local winds, as well as particulate size, control the footprint (e.g., the ash fall region of Sketch 8-3) for deposition of the ash, a footprint that can extend over a substantial area much bigger than the mountain. Biological exposure is by the same processes discussed for ejection of scoria and cinders in the formation of the cone, and suggested processes are shown in Sketch 9-1; however, density of contamination would be much reduced. This reduction is a result of few containers being at risk and much dilution. Dispersal of such ash plumes seems reasonably well understood (Link et al.,1982).

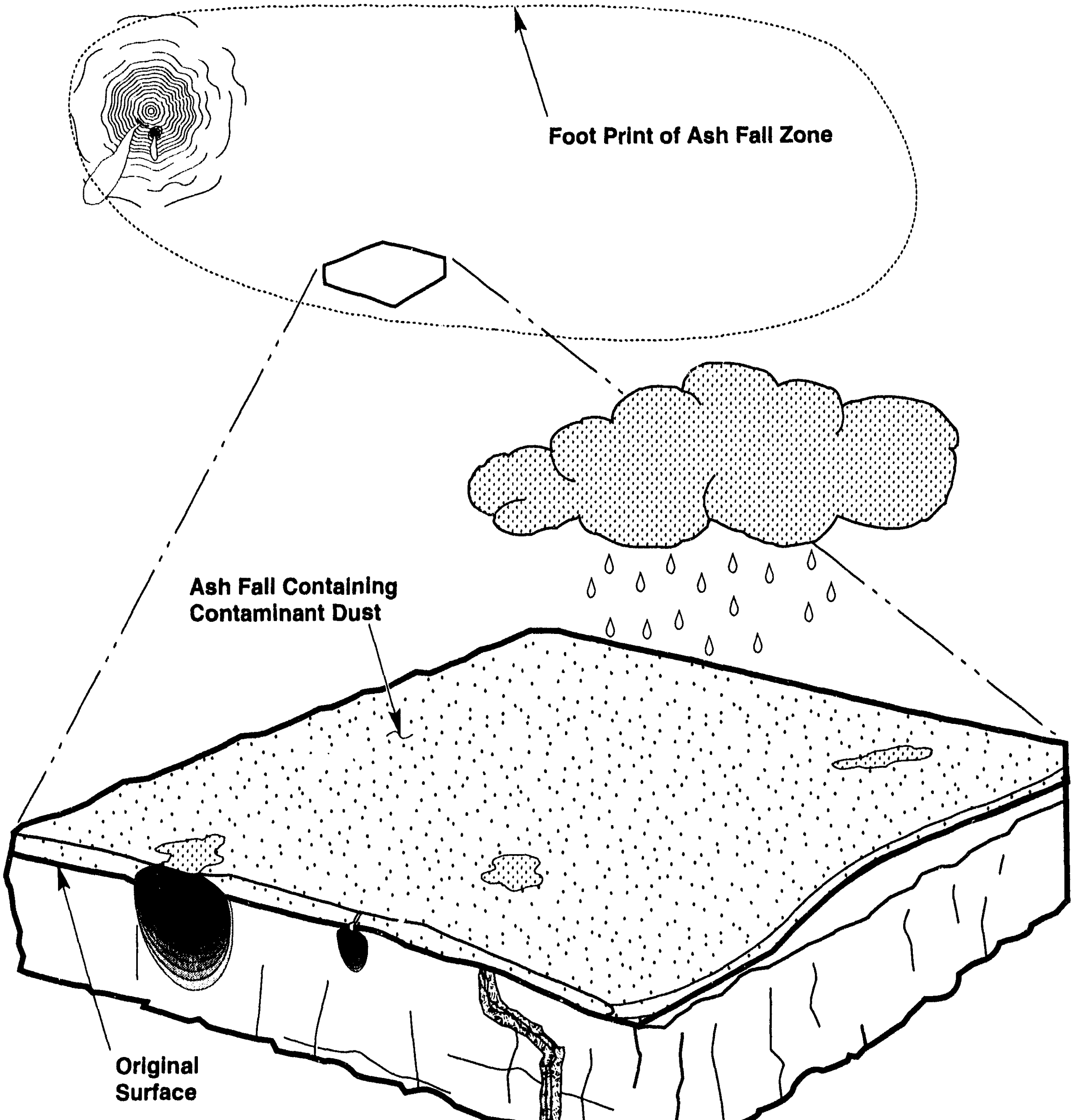
As before there is a direct exposure scenario ⟨9-1⟩, similar to the previously described branch of the same name in (TS2).

To continue, we first consider the case of contaminants from the ash fall deposit mobilized by percolating water. Ash fall deposits are known over a considerable range of variation in thickness; however, our paradigm is a cinder cone like Lathrop Wells Cone. This suggests depositional thicknesses of tens of centimeters at most. Precipitation percolates through this layer, contacting fine particulates containing contaminants. Whether percolation is down fractures or as unsaturated flow will depend on details of formation of the ash fall (which affect temperature, water content, etc.). Sketch 9-2 illustrates the processes. Because transport to the water table, save for reexposed contaminants, must pass through the flow system for the rocks under the ash fall and therefore involves hydrologic detail, we are representing these processes simply as ⟨9-2⟩, to be resolved in more detail if necessary.

The corresponding branch for contaminants affected by singular events (rapid snow melt, runoff from thunderstorms) has a number of possible shorter paths to biological effects. Clearly this expansion is similar to the expansion for Waste Fragmented and Entrained δ_1. Our general understanding is that the source has changed in the sense of dispersal, contaminant density, and encapsulation in the rock (now ash fall), but the fate of radionuclides after mobilization from the source is essentially the same. We therefore appeal to the same arguments offered earlier and list ⟨9-3⟩ through ⟨9-7⟩. Those possible scenarios in which the contaminants act as a source for the unsaturated flow system to transport mobilized radionuclides are ignored on the grounds of too long a residence time. However, in this case, if the ash fall covers areas where such transport is found to be more rapid or the distance much shorter, we will include such in the collection of scenarios.

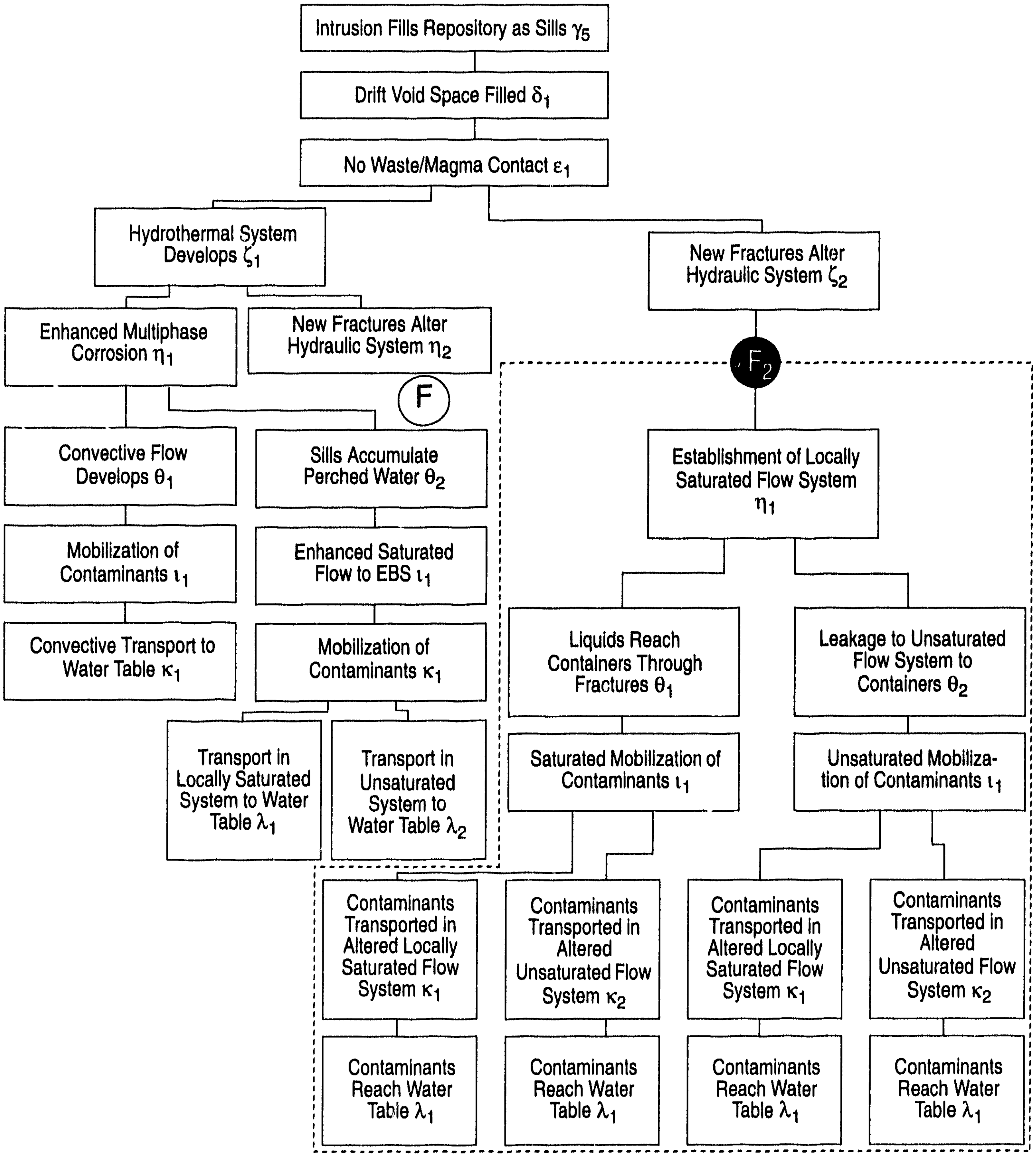


Sketch 9-1. Processes in an ash fall zone.



Sketch 9-2. Percolation through surface ash fall.

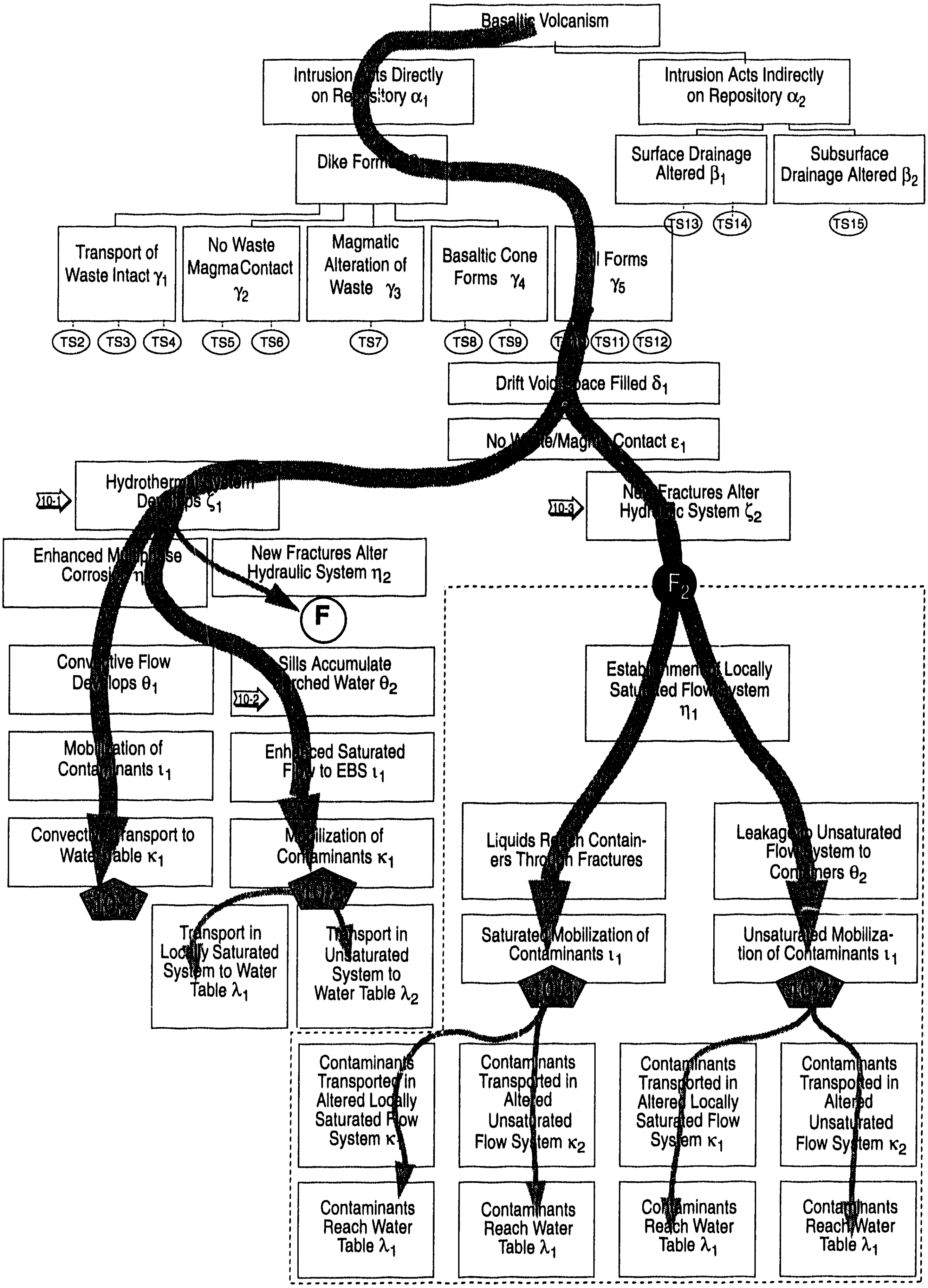
Formation of Sills ($\alpha_1, \beta_1, \gamma_5$)



Tree Segment 10a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, sill forms γ_5, drift void space filled δ_1.

Drift Void Space Filled (TS10)

A sill is a horizontal or subhorizontal intrusion that occurs as an extension from a dike. It



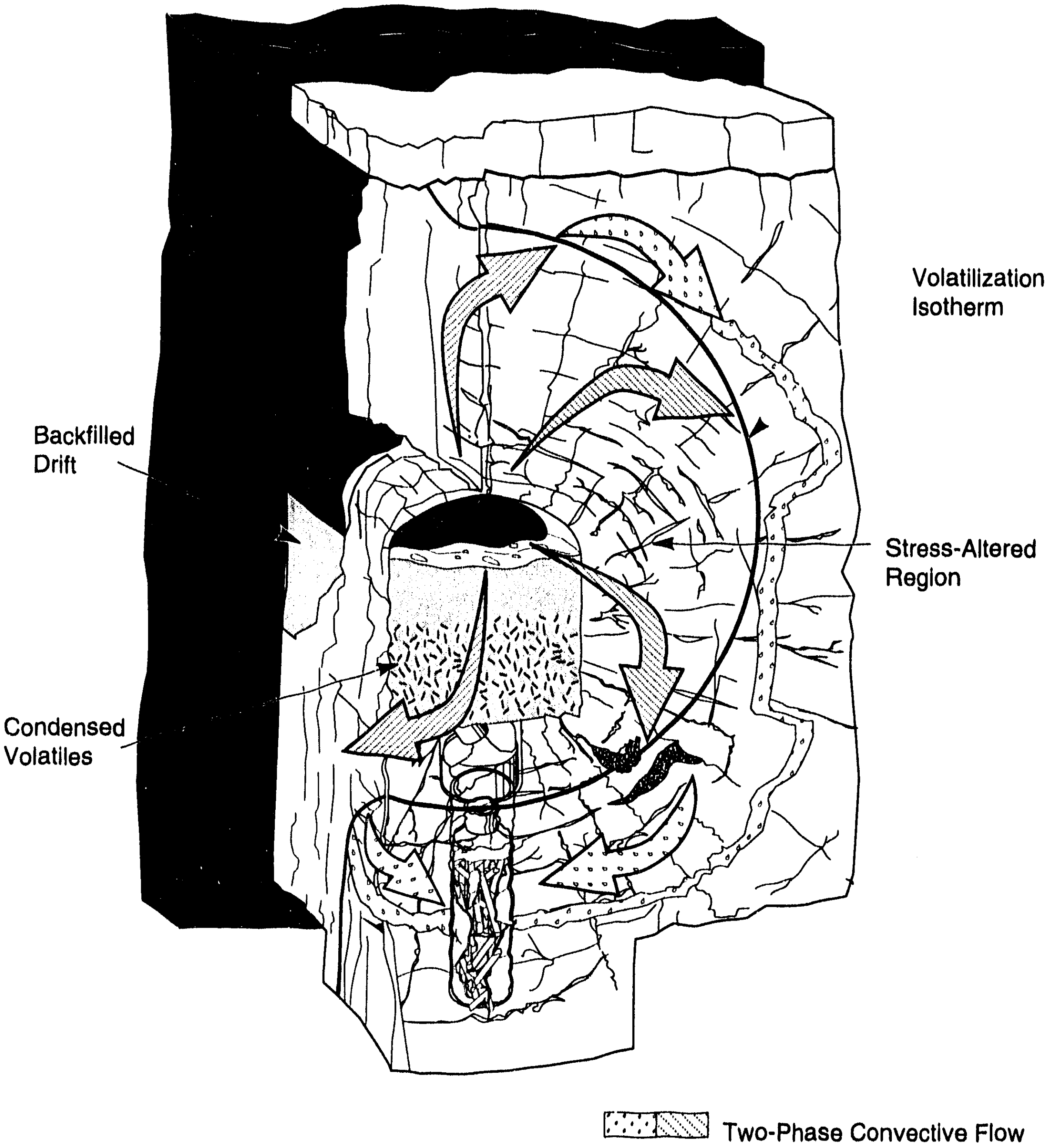
Tree Segment 10b. Scenario paths and scenario group paths of tree segment 10a.

is observed that a sill intrudes along a weakness and displaces (lifts) the overlying structure. According to data from two boreholes (Carr, 1982), two shallow sills are known to occur in Crater Flats. Our paradigm is the intrusion of a sill (or sills) along the horizon of the repository drifts. The paradigm dike, which feeds the sills, crosses the plane of the repository. In so doing it intersects the drifts and the stress-altered region around the drifts. We previously suggested two possibilities. The first possibility, shown in Sketch 1-2 and described in the branch Drift Void Space Filled δ_1, the subject of (TS10), is that the intrusion flows into the drift filling void space, thus relieving the driving pressure. The second possibility is that the intrusion not only flows into the drifts but causes fractures between drifts, thus forming a large tabular structure as in Sketch 1-3 and described in both Tabular Sill Bridges Between Drifts δ_2 (the subject of (TS11) and (TS12)), and Tabular Sill Hinged Model δ_3 (a variation of these two Tree Segments). Each of these δ branches considers three possibilities: one, there is no physical contact between magma and waste; two, that there is contact that alters the waste; and three, that there is contact which encapsulates the waste. We need to consider these details of the intruding sill because such details affect how the flow system interacts with the waste, and help establish what the source term (in the chemical sense) looks like.

We will first consider the case in which the sill forms in the drift void space. In the case of Drift Void Space Filled δ_1, the sill fills the void space in each drift cut by the dike to some distance determined by bulkhead spacing, by driving pressure and actual void volume; an example is shown in Sketch 1-2. A void volume will exist, even if the drifts are backfilled, because drifts cannot be refilled to original density but will have a residual density of around one half that of the surrounding country rock. Settling and bulldozing by the flow will allow penetration into some part of the void space. The net effect is a cap over the containers, on the order of five to ten meters away. For some alternative emplacement modes the containers could be suspended in the sill; such circumstances are specifics for detailed modeling and are not illustrated here.

One possibility is that the sill occurs or extends below the drifts to include the waste containers. At present it seems more likely that the location of the sill will be biased by the drifts, but the possibility of encapsulation of containers needs further consideration. We note that for our choice of paradigm the presumption is no physical contact between waste and magma. The presence of the stress-altered region around the drifts and the containers allows for a more complicated interaction to occur, at least in speculation. Whether there can in fact be such interaction is a matter for calculation and experiment.

Following (10-1), we observe the infilling of void space (δ_1) with No Waste/Magma Contact ε_1 illustrated in Sketch 10-1. The interaction is limited to thermal effects (Hydrothermal System Develops ζ_1) produced by the magma and to chemical interactions with any volatiles from the magma (e.g., SO_2, H_2S, H_2O). A volatilization isotherm is shown around an intrusion in the drift and reaching the containers. This cartoon includes fractures caused by emplacement of the drift. We expect heat transfer (primarily conduction) to initially close fractures, as is the case when the repository is initially loaded, and then during cooling produce additional fractures. Backfill, being of a lower density than the country rock, should act as a heat conduction barrier mitigating the thermal excursion at the containers. If the temperature of the containers is elevated enough to cause release of volatiles it is likely they will migrate laterally, probably condensing along fractures in the stress-altered region, with some volatiles possibly disseminated in the backfill when the sill has cooled. This dispersal is also shown in Sketch 10-1. The region of condensation is a concern only because it moves some contami-



Sketch 10-1. Heat from an intrusion reaches containers causing plate-out of volatiles. Mobilization of plate-out occurs as volatilization isotherm regresses.

nants out into the flow system away from the sill, so a threat may exist, even if the sill protects the remainder of the waste. Further development of this scenario requires some specification of how the flow system couples containers to the sill.

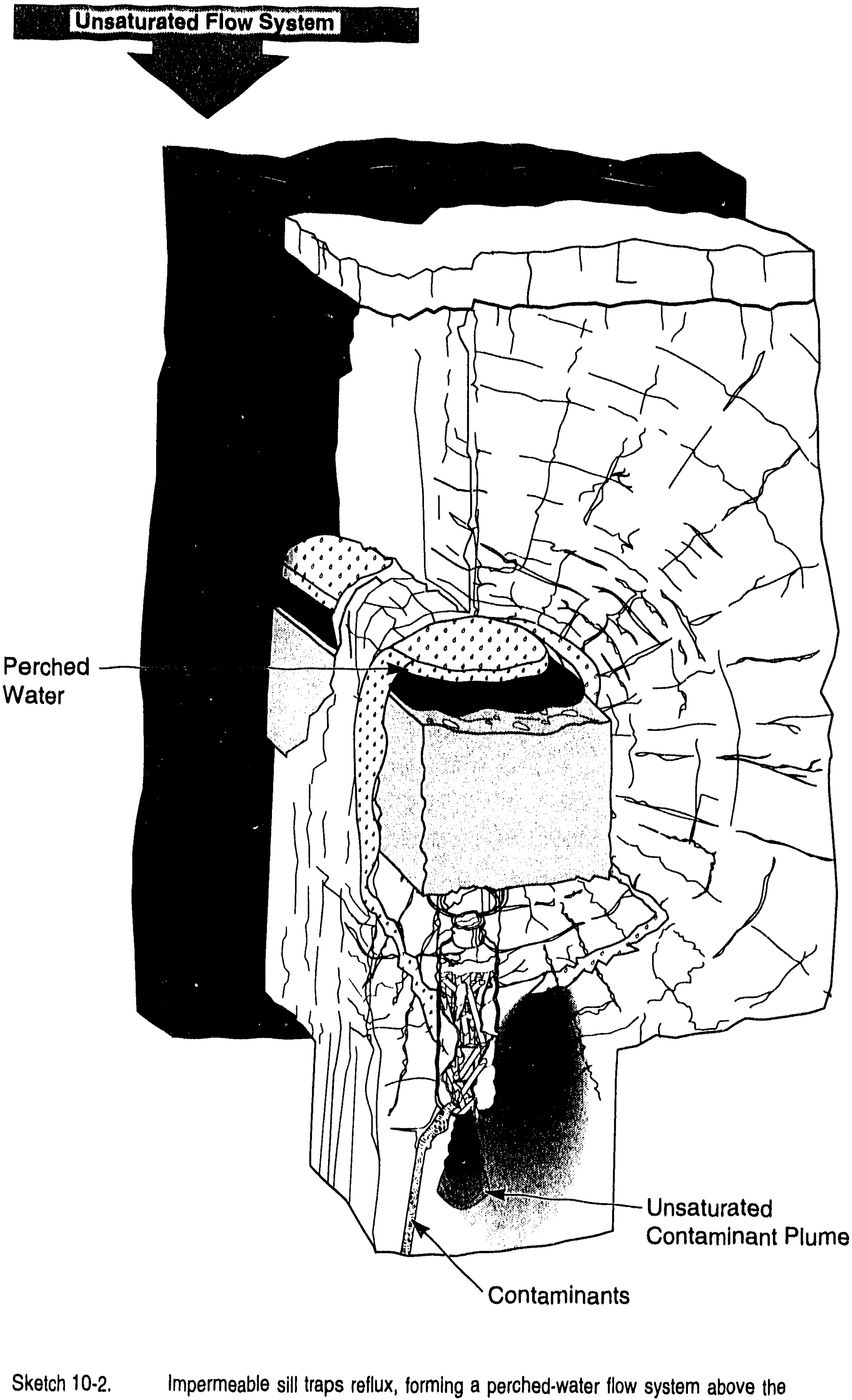
A heat source located above the region in which convective flow is established is a relatively ineffective driver of convection. Essentially the containers and waste are exposed to the return flow of a weak convective cell; most of the flow is above the sill. Be that as it may, the potential for flow to the containers, particularly a locally saturated return flow, remains. Corresponding mobilizing of contaminants by a locally saturated flow system and by an unsaturated flow system are in essence the same as those discussed and illustrated in connection with TS5 .

Because sills can be relatively impermeable, they could act as traps, capturing reflux atop themselves after pumping fluid above themselves and then cooling. This is the case in 10-2. Each sill-covered drift would then be the base of a perched water body able to bring fluids down to the repository either through cooling fractures or simply by deflection, as around the edge of an umbrella. We find these possibilities just barely plausible because of the volume of rock between drifts. We simply indicate the state of affairs in Sketch 10-2, and describe this relatively undifferentiated scenario.

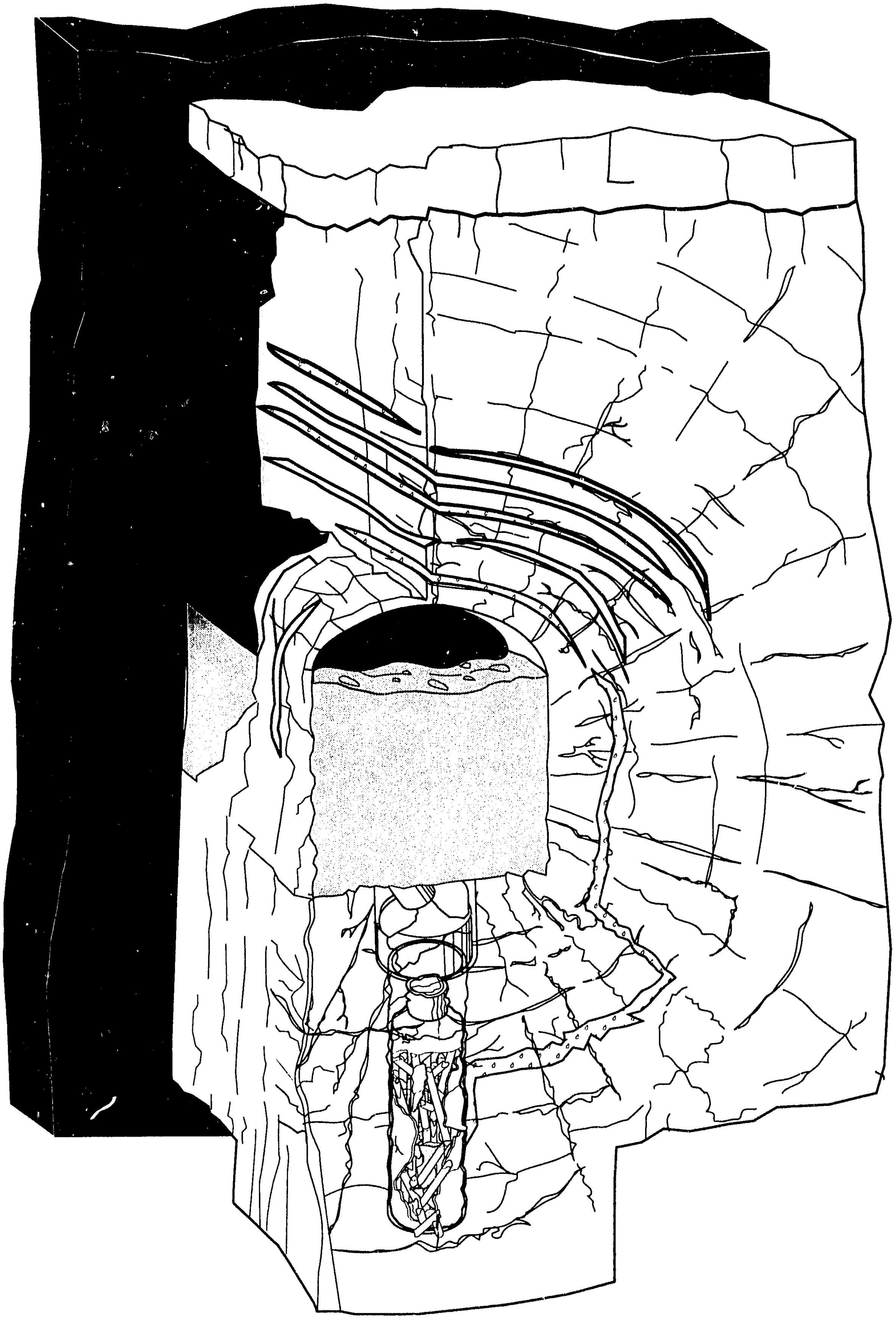
Referring to the Tree Segment 10 we have just been discussing, there is a second branch of No Waste/Magma Contact ε_1 labelled New Fractures Alter Hydraulic System ζ_2. We presume that, as in the corresponding case for the dike, the intrusion may produce a set of fractures parallel to the drift in which the sill has formed, and above the sill. The masticated backfill is less likely to support formation of such fractures. Sketch 10-3 shows the formation of a set of crown fractures resulting from insertion and subsequent cooling of the sill in the drift. If the flow system is unsaturated, these fractures would be a barrier to flow. For saturated flow, *e.g.*, the fracture flow of 10-3, in particular for the reflux flow from a condensation cap produced by a sill-driven two-phase convection, the fractures would offer paths around the sill. The flow could possibly reach the containers through connections to other fractures in the stress-altered region. The behavior of these crown fractures induced by the stress and thermal load of the sill in an already stress-altered region requires rather careful analysis.

The control of the source of fluids by fracture systems subparallel to the sill is the unusual feature here in these scenarios of 10-3 for the saturated case and 10-4 for the unsaturated case. Once the control is identified, the scenarios proceed with mobilization and transport similar to those described previously.

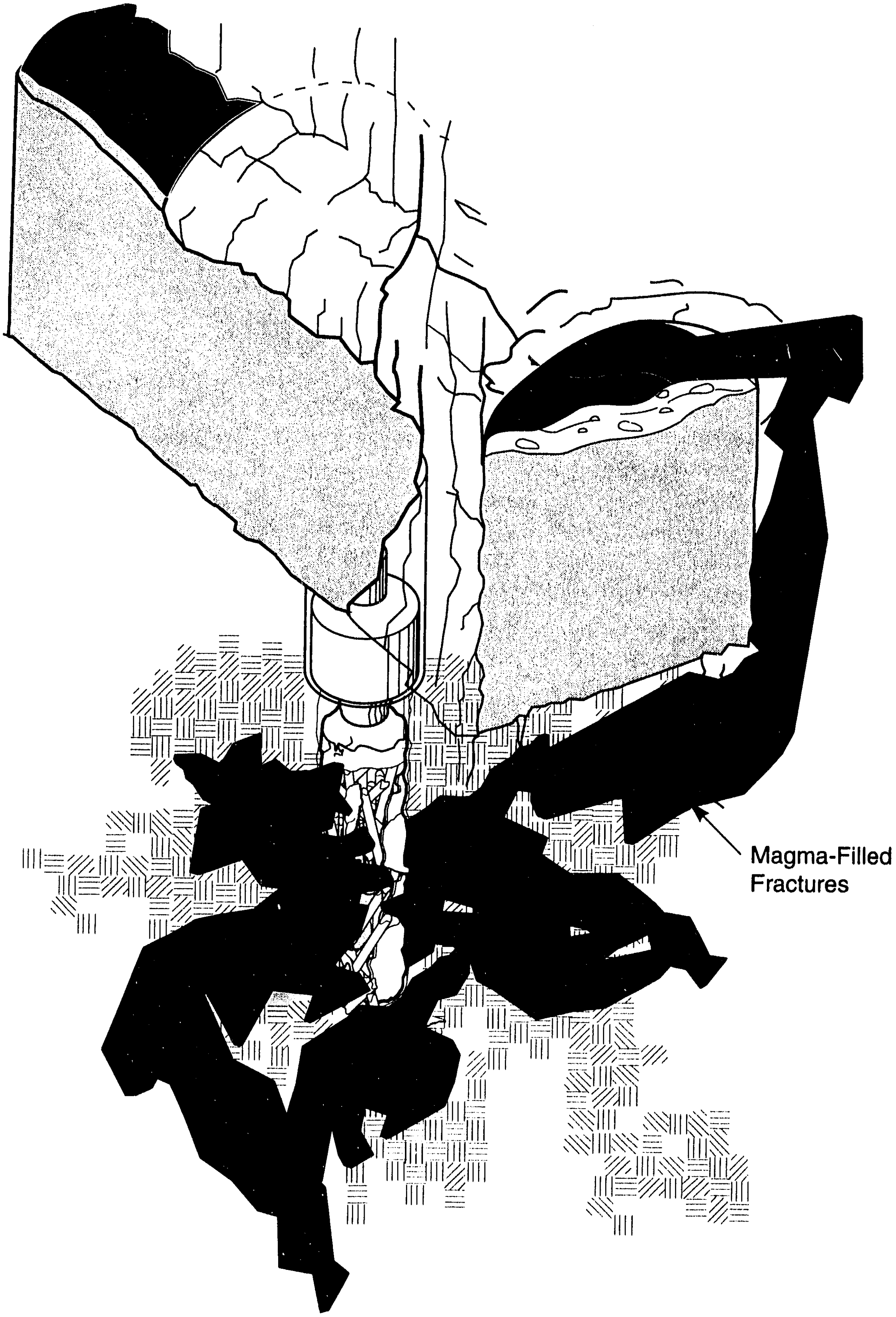
One possibility is that the sill occurs or extends below the drifts to include the waste containers. At present it seems more likely that the location of the sill will be biased by the drifts, but the possibility of encapsulation of containers needs further consideration. We note that for our choice of paradigm the presumption is no physical contact between waste and magma. The presence of the stress-altered region around the drifts which encompasses the containers allows for a more complicated interaction shown in Sketch 10-4 to occur, at least in speculation. Whether there can in fact be such interaction is a matter for calculation and experiment. If the drifts are filled as sills form, it is conceivable that magma and waste could come into contact in the following manner. Fractures associated with the stress-altered region and with emplacement could act as conduits allowing contact. Such conduits (the fractures) have a large surface area in contact with a substantial volume of rock. We expect that flow down any such fractures will chill rapidly and freeze in place before reaching the waste, particularly if the backfill in the drifts becomes involved. Therefore, although



Sketch 10-2. Impermeable sill traps reflux, forming a perched-water flow system above the sill.



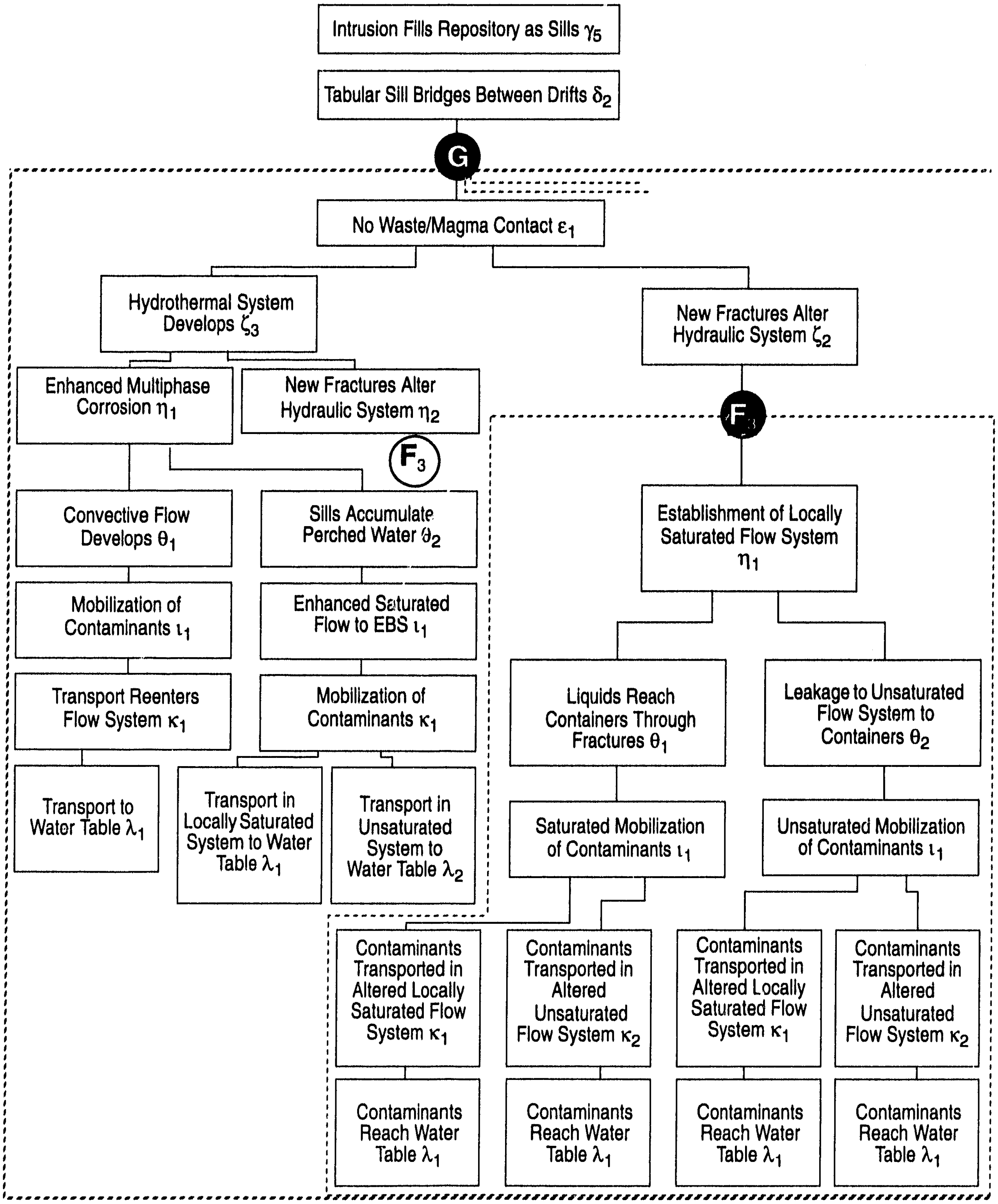
Sketch 10-3. Crown fractures form above drift-filling sill and alter hydraulics.



Sketch 10-4. Magma reaches waste through fractures formed upon driving of drift.

a number of scenarios could be constructed using fracture conduits to fill the container and waste void spaces with magma, the magma entering fractures will likely cool to form apophyses rather than continuing along the fractures.

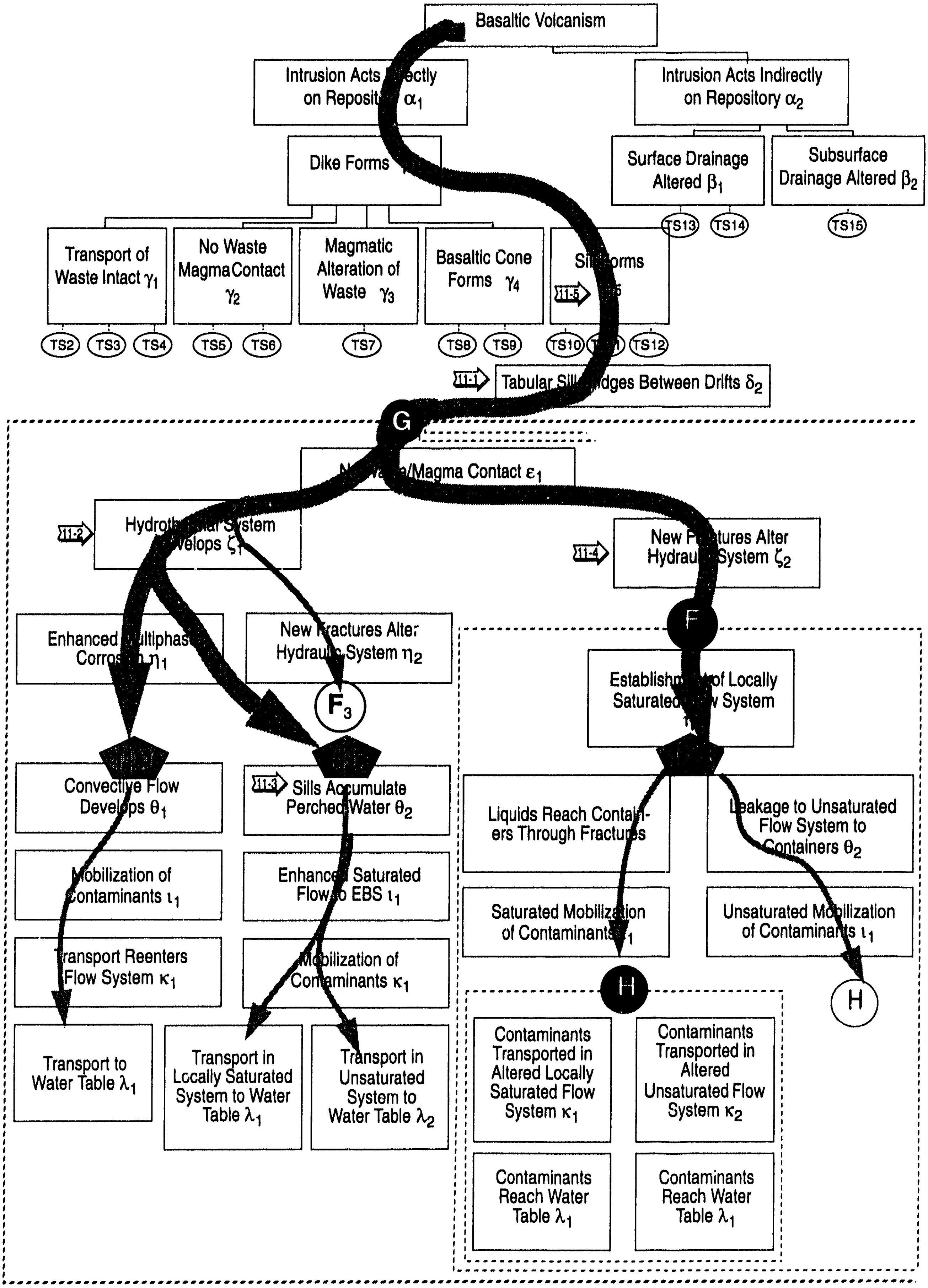
There is an additional feature of sills near the repository that requires consideration, but which we leave to the modeling. Igneous intrusions exolve volatiles (H_2S, CO_2, CO, H_2SO_4, H_2O, HF) during emplacement, which may be extremely hostile to waste containers. Transient interaction of these volatiles and the repository can occur even if the intrusion is so far above or below the waste containers that the intrusion does not itself contact containers.



Tree Segment 11a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, sill forms γ_5,tabular sill bridges between drifts δ_2.

Sill Bridges Between Drifts (TS11)

Earlier in the discussion of sills we mentioned two possible models of sill formation, both



Tree Segment 11b. Scenario paths and scenario group paths of tree segment 11a.

of which produced a tabular structure as in Sketch 1-3, connecting several drifts. We return to that discussion, referring to Tree Segments 11 and 12.

In the tabular sill cases, we presume a preferential fracturing in the plane of the potential repository drifts because of stress and strain interactions between neighboring drifts (Brady et al., 1985; Serata, 1974). The space filled by the sill is created by a wedging of the overburden accompanied by fracturing perpendicular to the sill flow direction. Sketch 11-1 shows the tabular sill with perpendicular fractures in the overburden as a result of the intrusion.

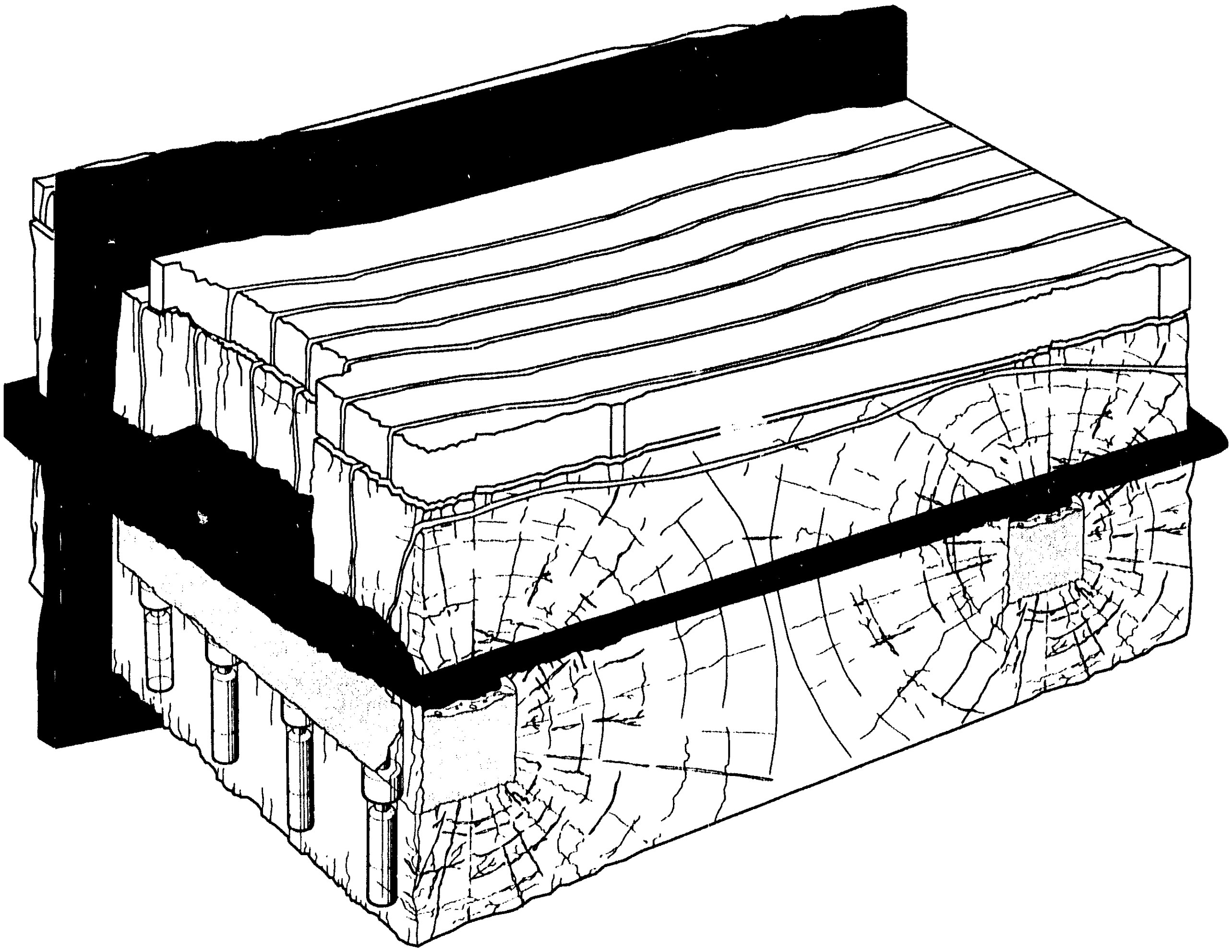
To expand the No Waste/Magma Contact ε_1 part of this branch of the tree, we first follow 11-1. In the case of Tabular Sill Bridges Between Drifts δ_2, we are, as in the case of Sill Fills Drift Void Space δ_1, trying to drive a convective system from above. The sill forms a hot cap. Convective flow of fluid above the sill reaching the containers below can occur only at the edges of the sill. The behavior of the flow system, convection and reflux, necessary to provide fluids to the containers is shown in Sketch 11-2. Recall also the vertical fracturing, caused by inflation during insertion of the sill. These fractures in overlying beds, while not extending to the surface, provide pathways for rapid flow of vapor away from the sill. When the sill is cool, these same fractures should provide barriers to unsaturated flow (capillary flow) and conduits for locally saturated flow. Interactions of the fluids with the containers and contents are similar to previously discussed models. Saturated and unsaturated mobilization and transport are sufficiently intertwined here that we will leave any differentiation to the modeler for resolution.

We continue to 11-2, which includes scenarios involving perched water. In Sketch 11-3 we see the possibility that fluids could accumulate on a cool sill, reaching the waste containers through fractures in the sill, by flow around the sill, or simply by unsaturated leakage through the sill. Such circumstances show a mass of perched water accumulated on the sill. We intend to allow for episodic accumulations and flow as well as pseudo-equilibrium flow. Clearly, full modeling of such perched water requires a complete specification of sill flow properties, including fractures and characteristic curves.

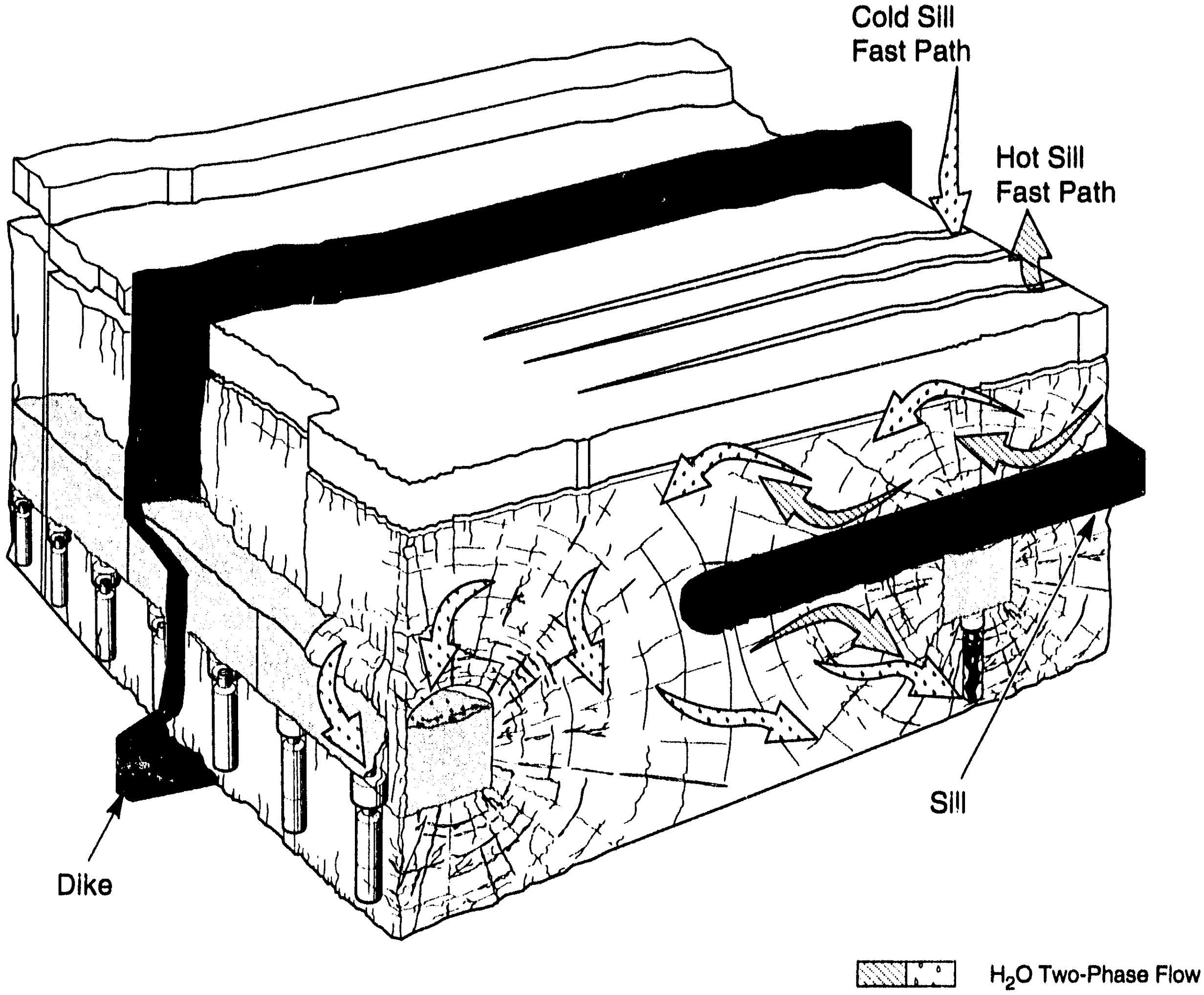
Our reference tree has a branch parallel to Hydrothermal System Develops ζ_1 in Tree segment 11: namely, New Fractures Alter Hydraulic System ζ_2, along 11-3. Some of those new fractures are indicated in Sketch 11-4. We are presuming a sill cold enough to allow return of liquid in the unsaturated and in the locally-saturated flow fields. For the unsaturated flow, the presence of these roughly orthogonal sets of fractures will provide capillary barriers to flow with possible episodic fracture flows, producing essentially local, transient perching atop the sill. Such perched water is then the source for locally saturated flow around the sill or down cooling fractures through the sill.

Determination of actual behavior is so dependent on data that have yet to be collected and analyzed that we forgo a more detailed expansion of what we expect to be second-order contributions to contaminant mobility. Accordingly, the group of scenarios of 11-3 is noted, but not discussed further.

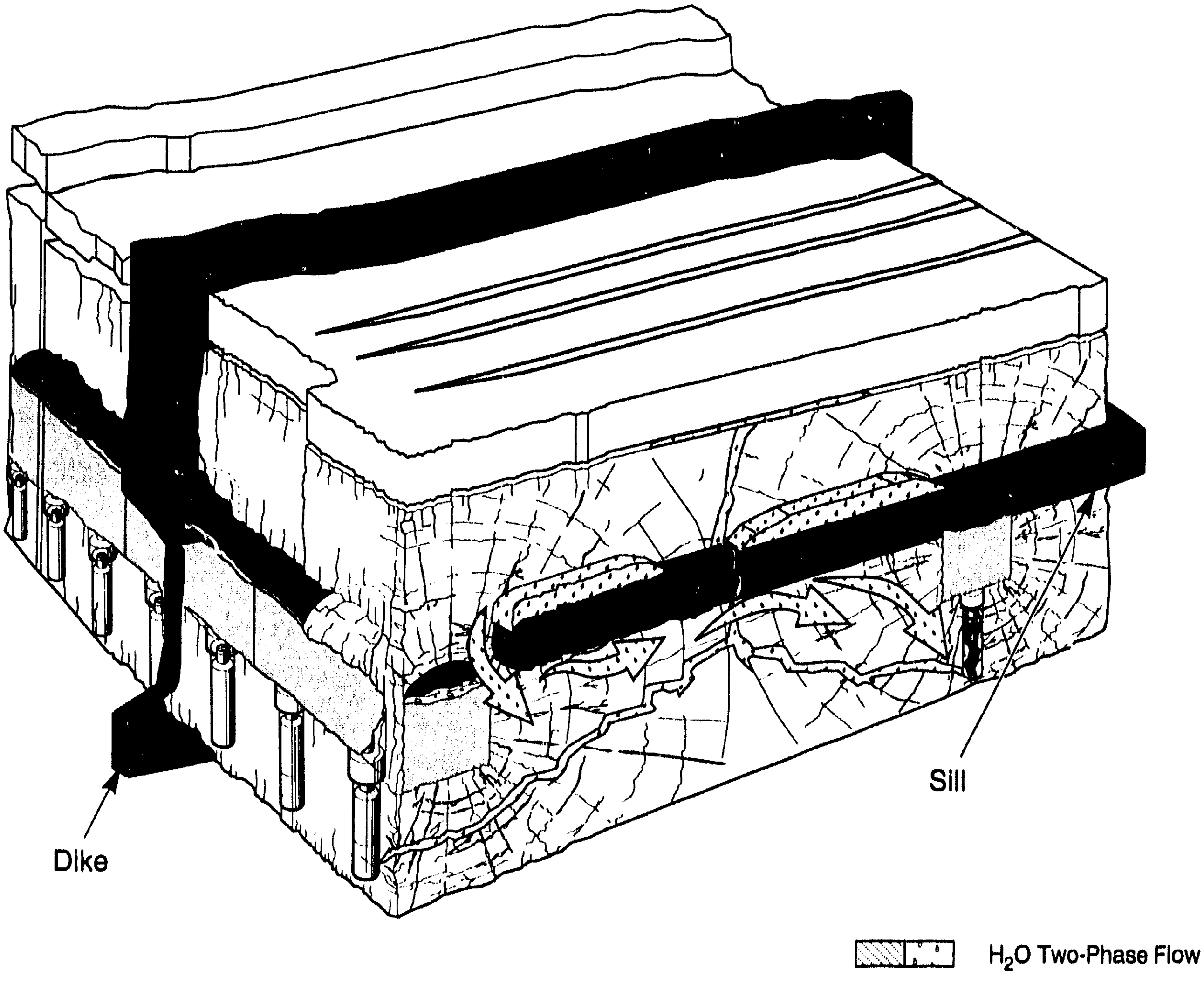
A cross-sectional view of the mountain showing the emplacement appears in Sketch 11-5. It is unclear that a sill much below the waste or much above the waste could cause an increase in radionuclide releases to the accessible environment. However, as remarked above, there is some possibility for interaction of aggressive volatiles from the magma with waste containers. The threat is transient and we do not yet have data on how close the sill must be to containers for the threat to be significant.



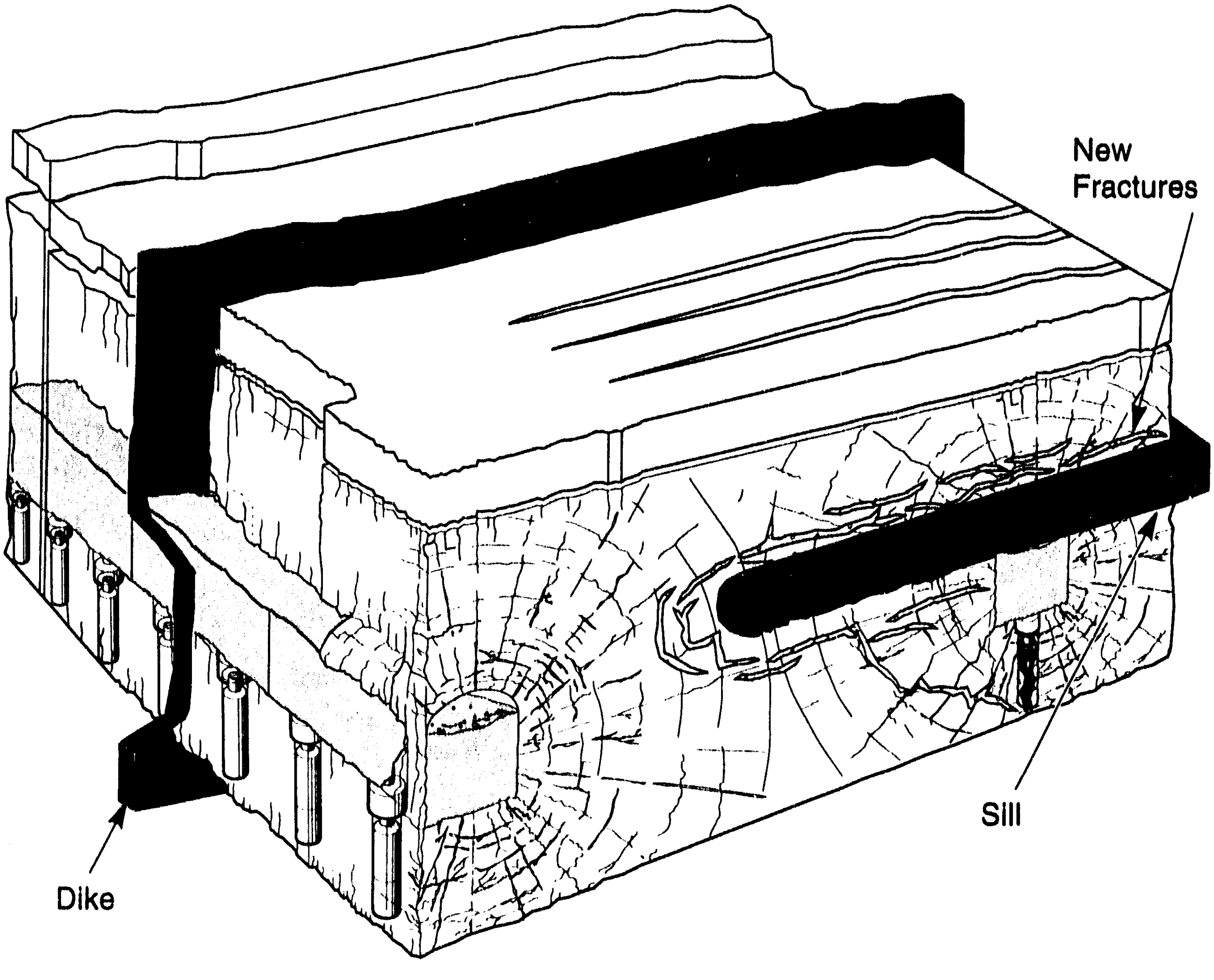
Sketch 11-1. Tabular sill bridges between drifts and fractures overburden upon insertion.



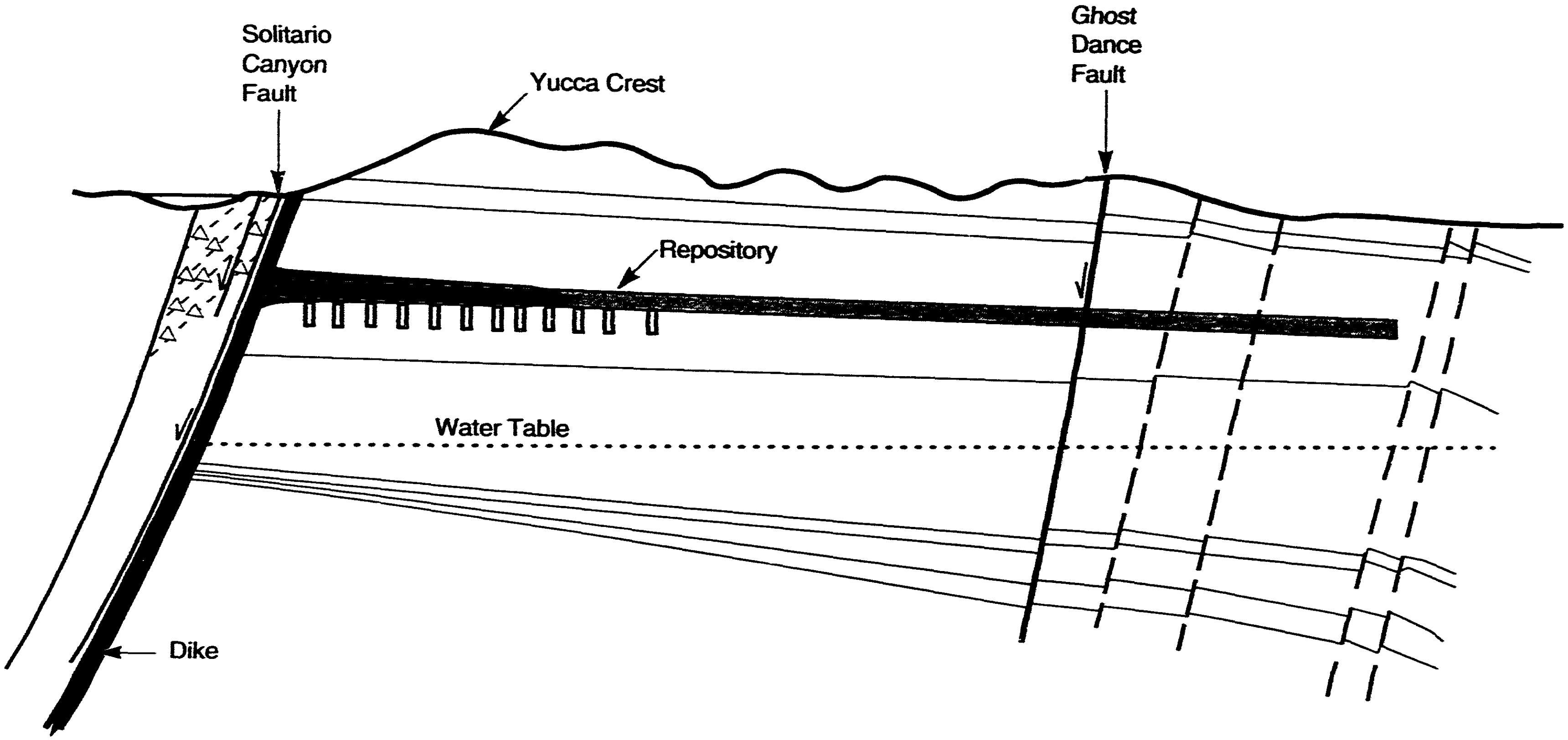
Sketch 11-2. Two-phase flow from hot dike and possible pathways to containers and waste, including fast path away from sill through fractures.



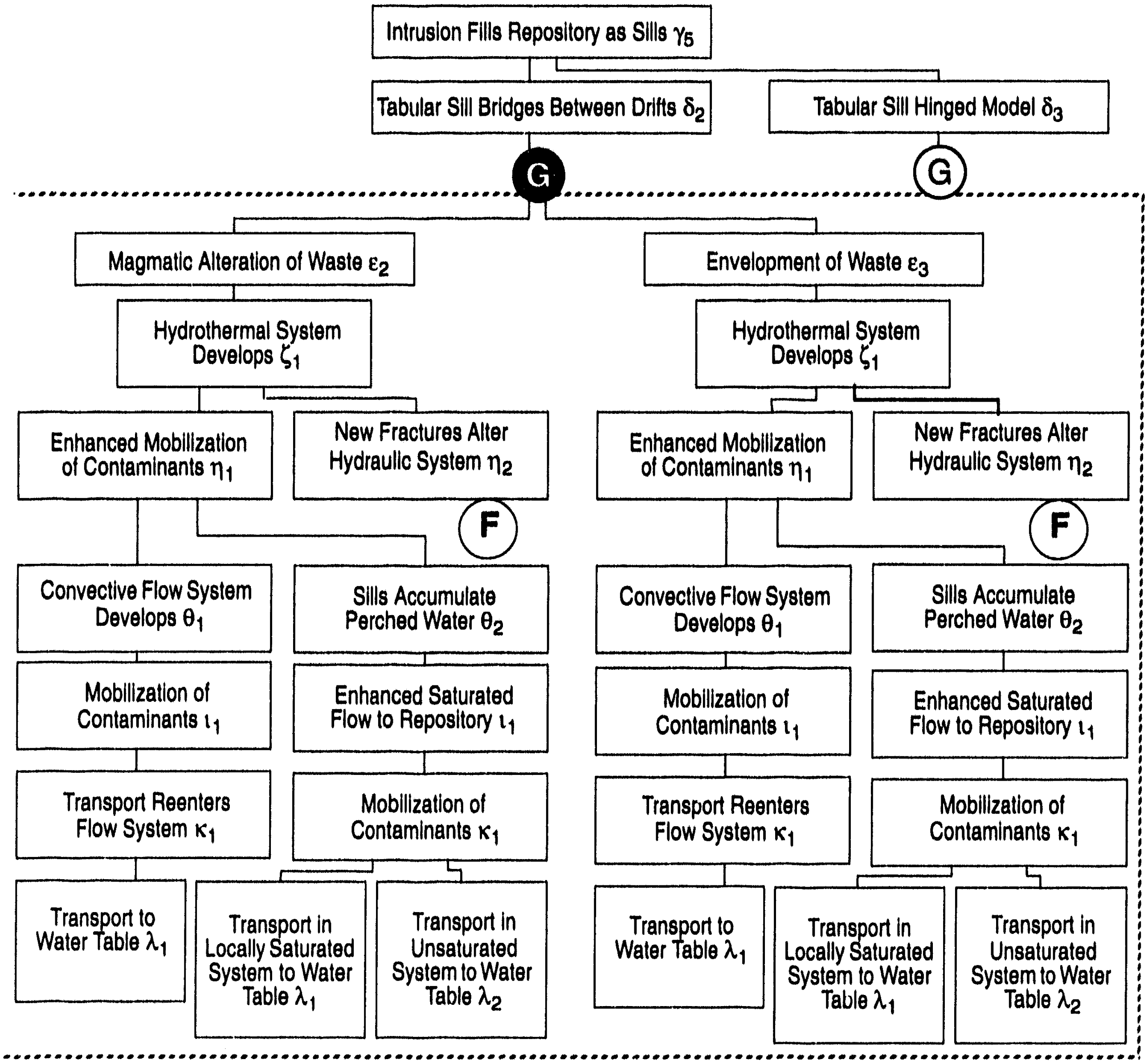
Sketch 11-3. Ponding on sill and subsequent possible water pathways to containers.



Sketch 11-4. New fractures in the overburden parallel to sill alter flow.



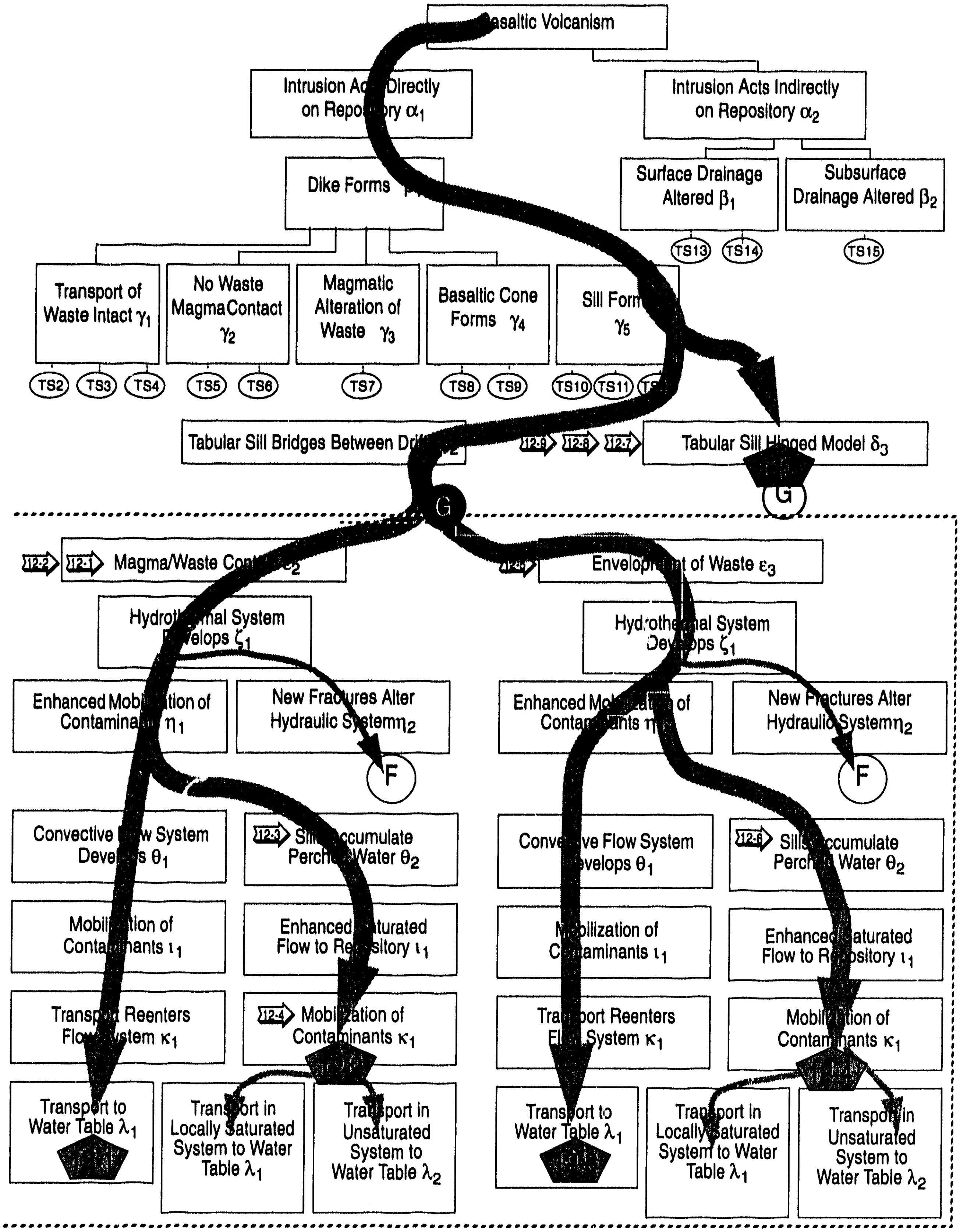
Sketch 11-5. Cross sectional view of Yucca Mountain with sill emplaced in drift horizon (after Scott and Bonk).



Tree Segment 12a. Basaltic volcanism, intrusion acts directly on repository α_1, dike forms β_1, sill forms γ_5, tabular sill bridges between drifts δ_2, magmatic alteration of waste ε_2, and envelopment of waste ε_3.

Tabular Sill Bridges Between Drifts (TS12)

This leaves us with the discussion of direct interaction between waste and magma in Tree Segment 12. Two branches are distinguished in this Tree Segment, Magmatic Alteration of Waste ε_2 and Envelopment of Waste ε_3. These branches were of little importance earlier, in the model where only the drift void space was filled, because the total volume of magma available in the sill was no more than half a drift volume every 40 meters. In the case of Tabular Sill Bridges Between Drifts δ_2, at least five or six times that volume of magma is available, making more thermal energy available to heat the waste containers. This would imply higher temperatures in the rock over a larger rock mass. Under these circumstances we need to consider magmatic fluid flow through the stress-altered region around the drifts, including the container-



Tree Segment 12b. Scenario paths and scenario group paths of tree segment 12a.

emplacement holes. We do not expect substantial physical transport of spent fuel by apophyses of sill running through the fracture system. Rather we can suggest fracture-filling apophyses intersecting the emplacement hole, a hole that is simply a vug with spent fuel and container as a filling. Even for a substantial sill, these apophyses should chill rapidly because of the large surface area. If there is any movement of contaminants, it is into connected fractures as a network of contaminated fracture filling. This set of circumstances we describe with Sketches 12-1 and 12-2, which represent basalt magma leakage driven down a set of fractures to the container. Recall that fractures have small apertures, so magmatic flow is limited by heat transfer and is not likely to proceed very far. Also, these small apertures limit the size of spent-fuel debris that can be carried anywhere. In all likelihood the net result is a source distributed over a modestly larger volume than a container, but a source surrounded in chilled magma. Water flow will reach this waste with difficulty after connecting fractures are closed by the magma. We have identified a scenario described in 12-1

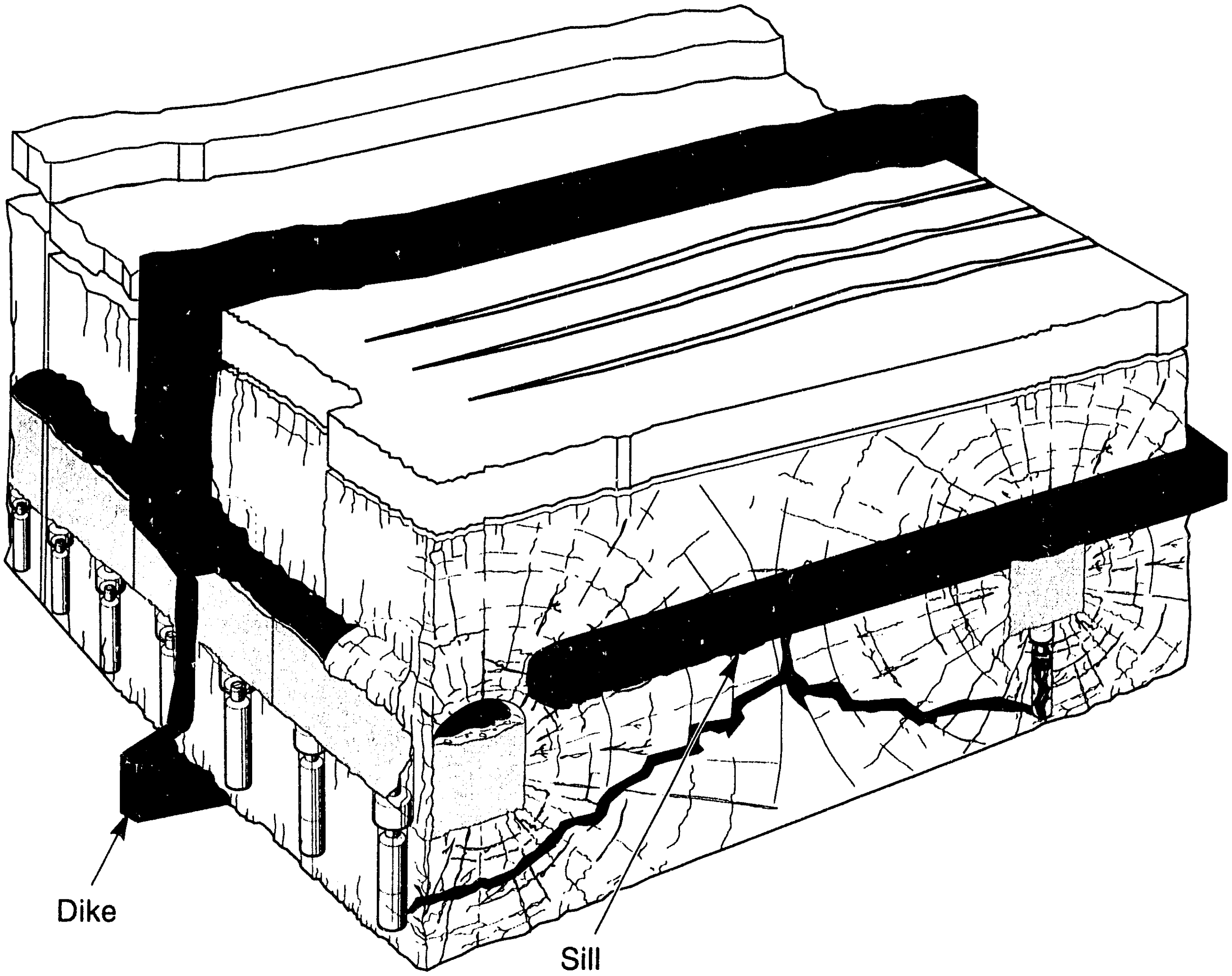
Since the sill, when cold and intact, has the potential for blocking flow, perched water could form over the potential repository. Our reference tree recognizes this possibility in 12-2 as a consequence associated with a hydrothermal system. Accumulation of perched water and the fracture sets caused by sill injection appear in Sketch 12-3. Those injection fractures could provide pathways for flow of accumulated, perched water to and around drifts to the waste containers. Interaction with the waste, which has interacted with magma from the sill, is shown in Sketch 12-4. This figure combines both locally saturated flow and unsaturated flow. Despite separation into two branches in the reference tree, this will be regarded as a scenario group with differentiation occurring in modeling of flow.

Tree Segment 12 considers New Fractures Alter Hydraulic System by reference to Ⓕ in addition to Enhanced Mobilization of Contaminants, as did Tree Segment 11 where the related discussion occurs.

Our paradigm for the scenarios presumed that insertion of the sill was biased by the presence of the drifts. It could be that the location of the sill is influenced by the first contact with the stress-altered region around the drifts. If so, we need to discuss intersection of the sill with containers even though it is not part of the paradigm. Because there is no outlet, the contents of the containers are entombed in the sill; these scenarios are in group 12-3. Movement of the spent-fuel debris depends on the thickness of the sill relative to container size. Sketch 12-5 includes a sill formation that intruded the spent fuel containers' horizon. We presume that container damage or already existing degradation will allow dispersal of spent-fuel debris along the sill and that void spaces where the emplacement hole sticks out of the plane of the sill will be filled with magma as well. Dr. Borns, in reviewing this document, suggested the sill could supply a secondary vent. We have not included such a possibility, because we don't know enough about the plumbing. This is a matter of concern which needs to be addressed further and possibly included as another scenario.

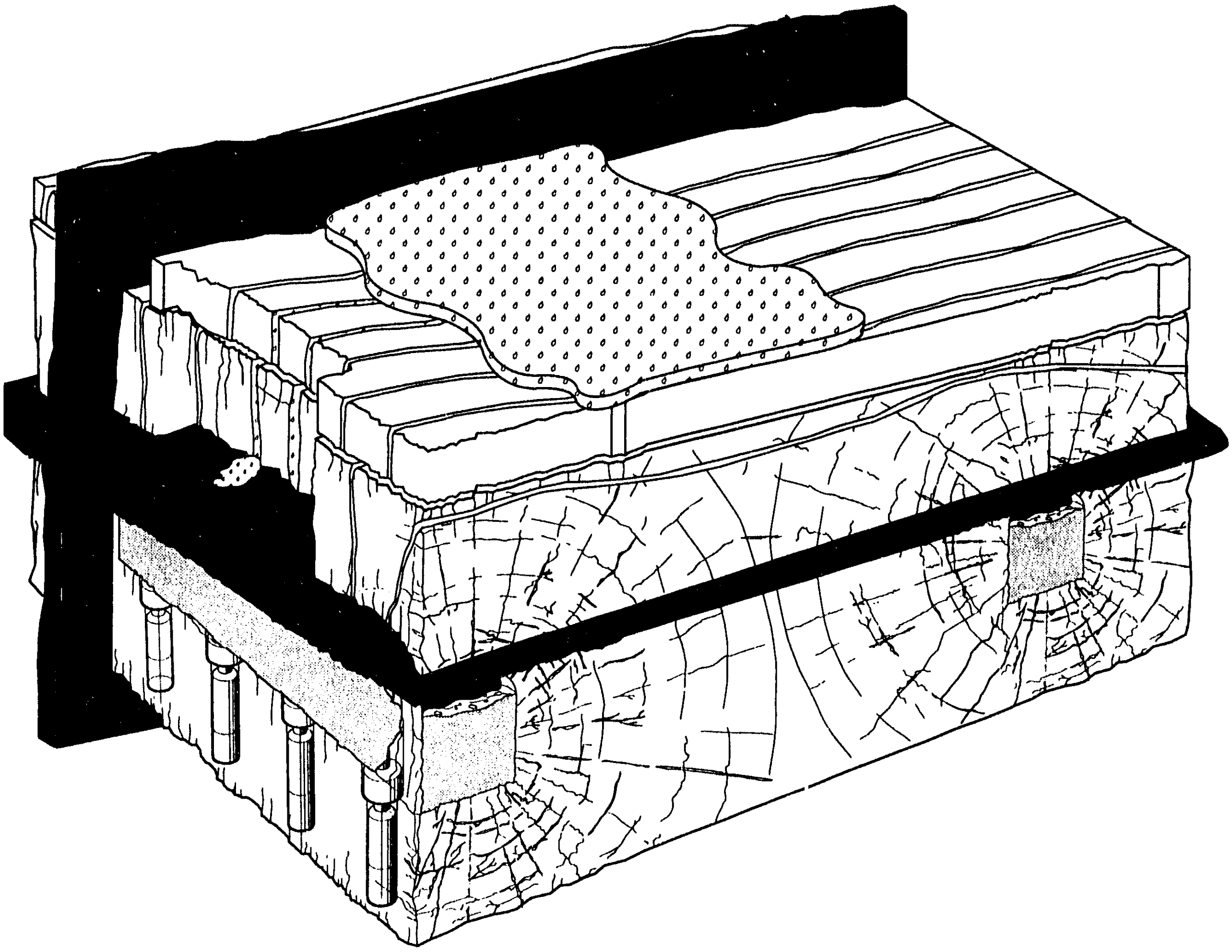
In 12-3 we have a two-phase convective flow system heated from the level of the containers. During the cooling phase of the sill, the most important contribution of fluids to waste containers seems to be off the edge of the sill where condensed fluids can flow to neighboring containers. This idea is also pictured in Sketch 12-5. No explicit distinction has been made between unsaturated and saturated transport in this path.

We next move to 12-4. As the sill cools and the flow system that was disturbed becomes reestablished, it is possible that perched water accumulates on the sill. This perching and subsequent flow are indicated in Sketch 12-6. Presumably the sizes of perched water bodies are

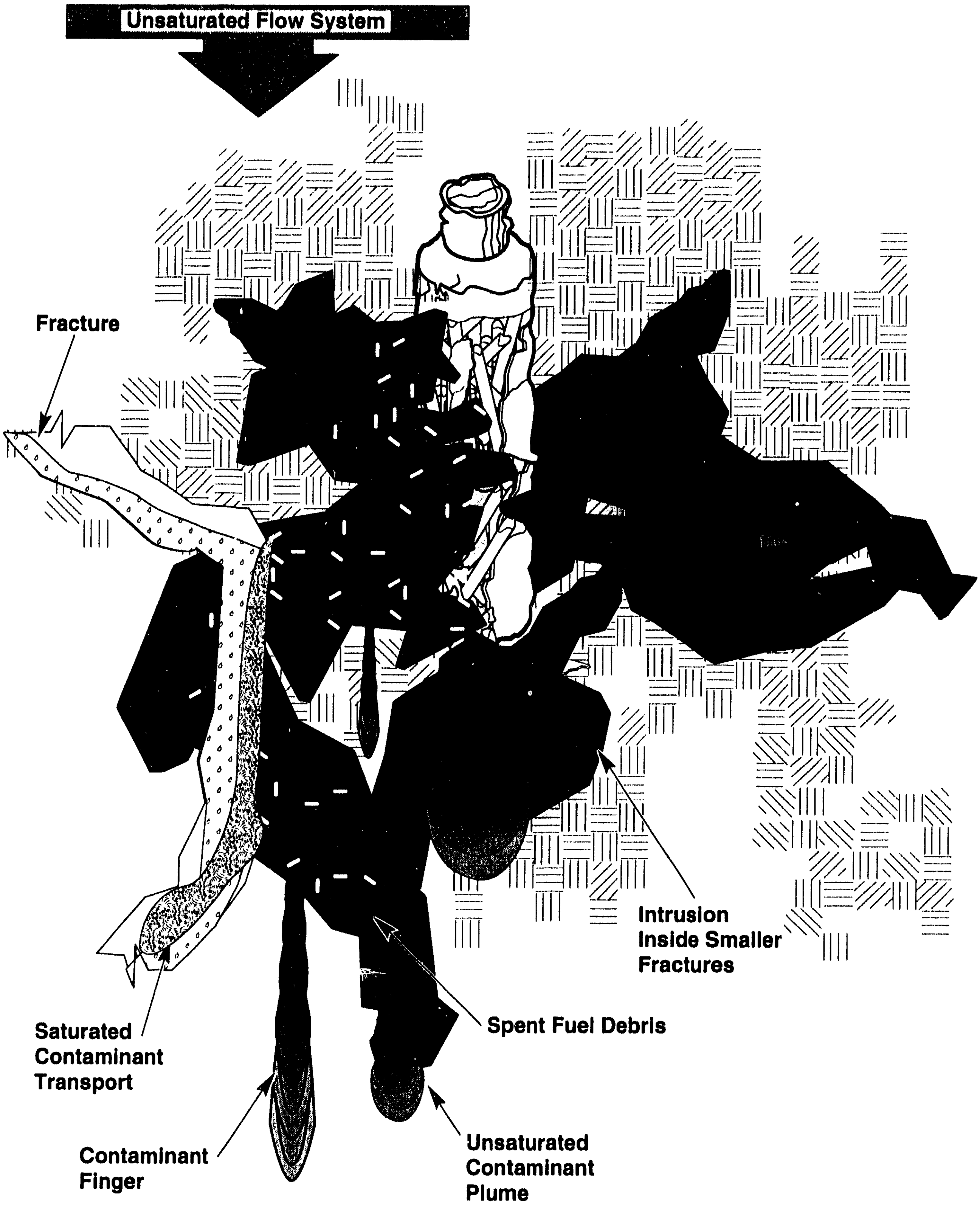


Sketch 12-1. Magma, extending from sill, reaches containers by traveling along fractures in the stress- altered region.

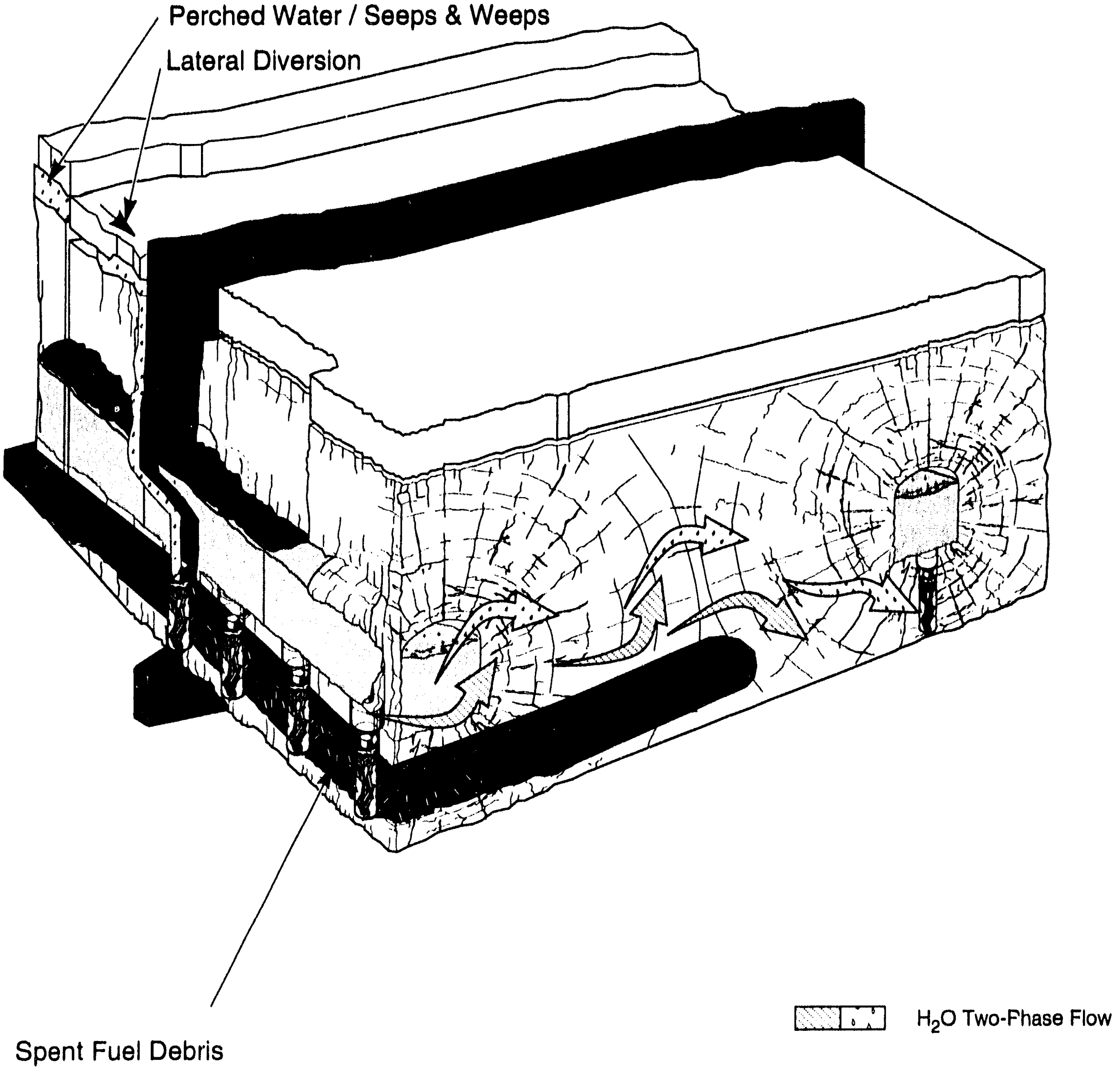
Sketch 12-2. Magma reaches container through small connected fractures and carries away contaminant debris from the container.



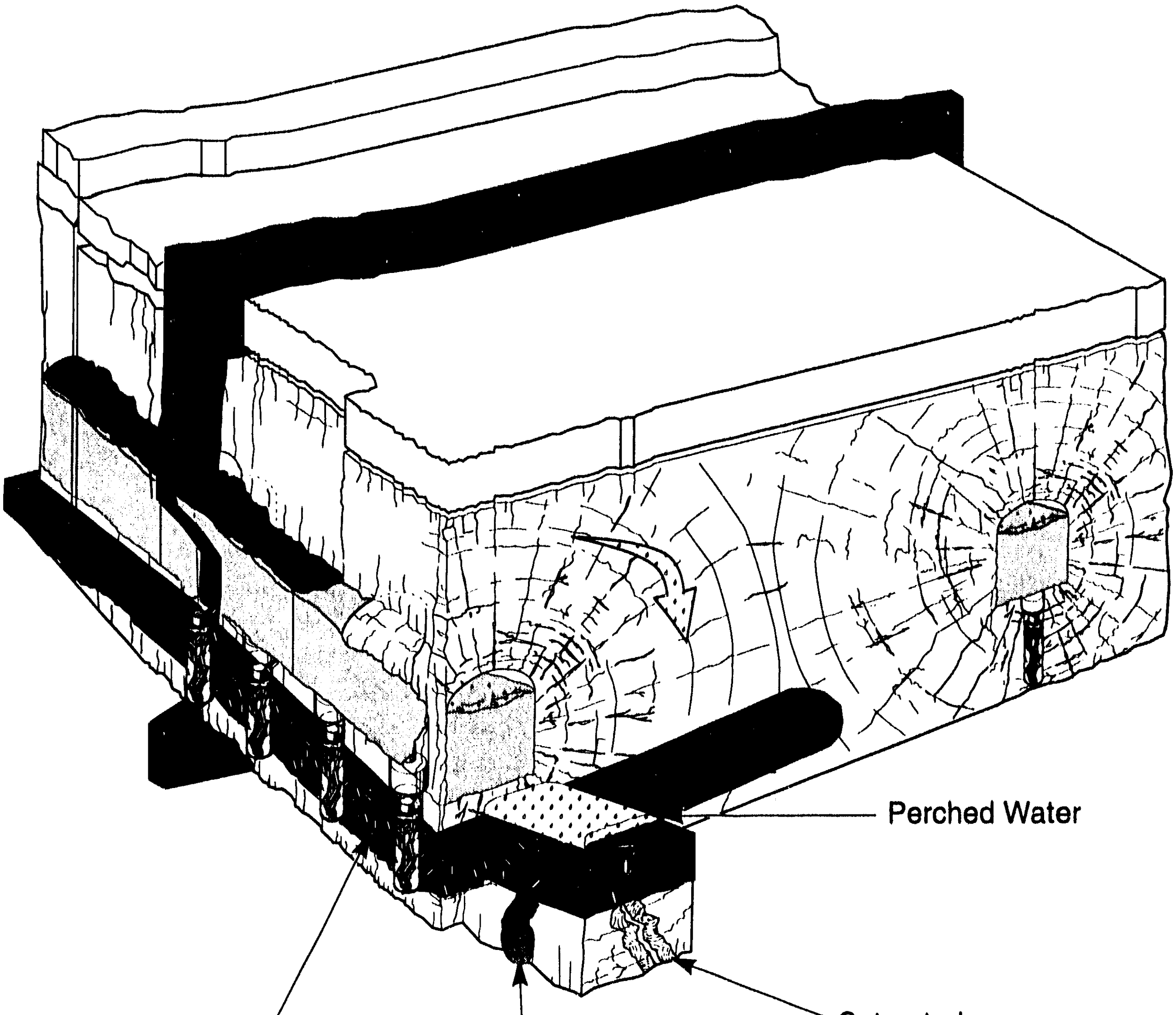
Sketch 12-3. Water accumulates along the fracture set resulting from sill injection.



Sketch 12-4. Spent fuel debris in apophyses is mobilized and contaminants are transported.



Sketch 12-5. Sill intrudes waste container horizon encapsulating spent fuel debris.

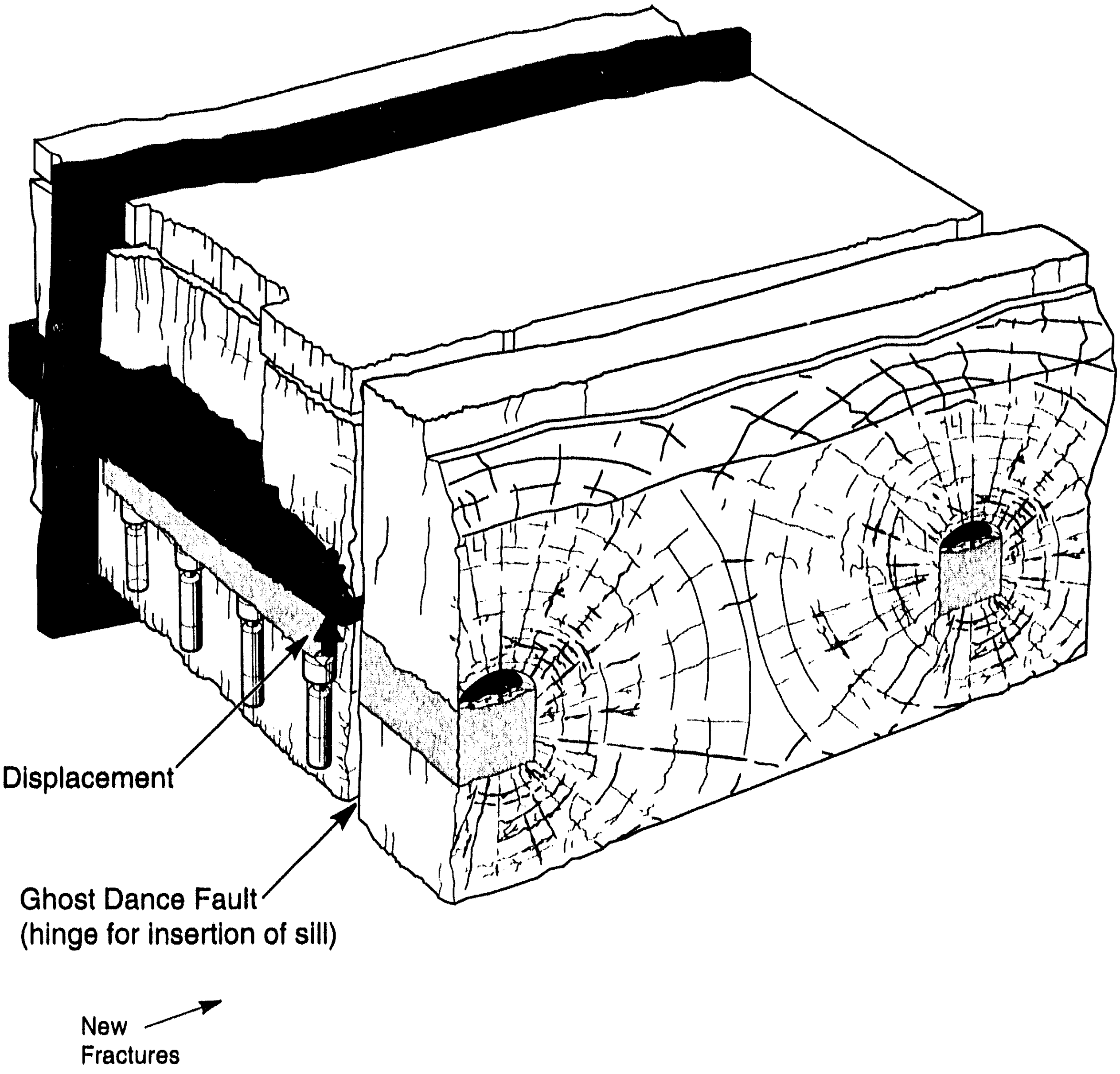


Sketch 12-6. Perched water accumulates on cold low permeability sill, finds pathways to contaminants, mobilizes waste, and transports waste contaminants to the saturated zone.

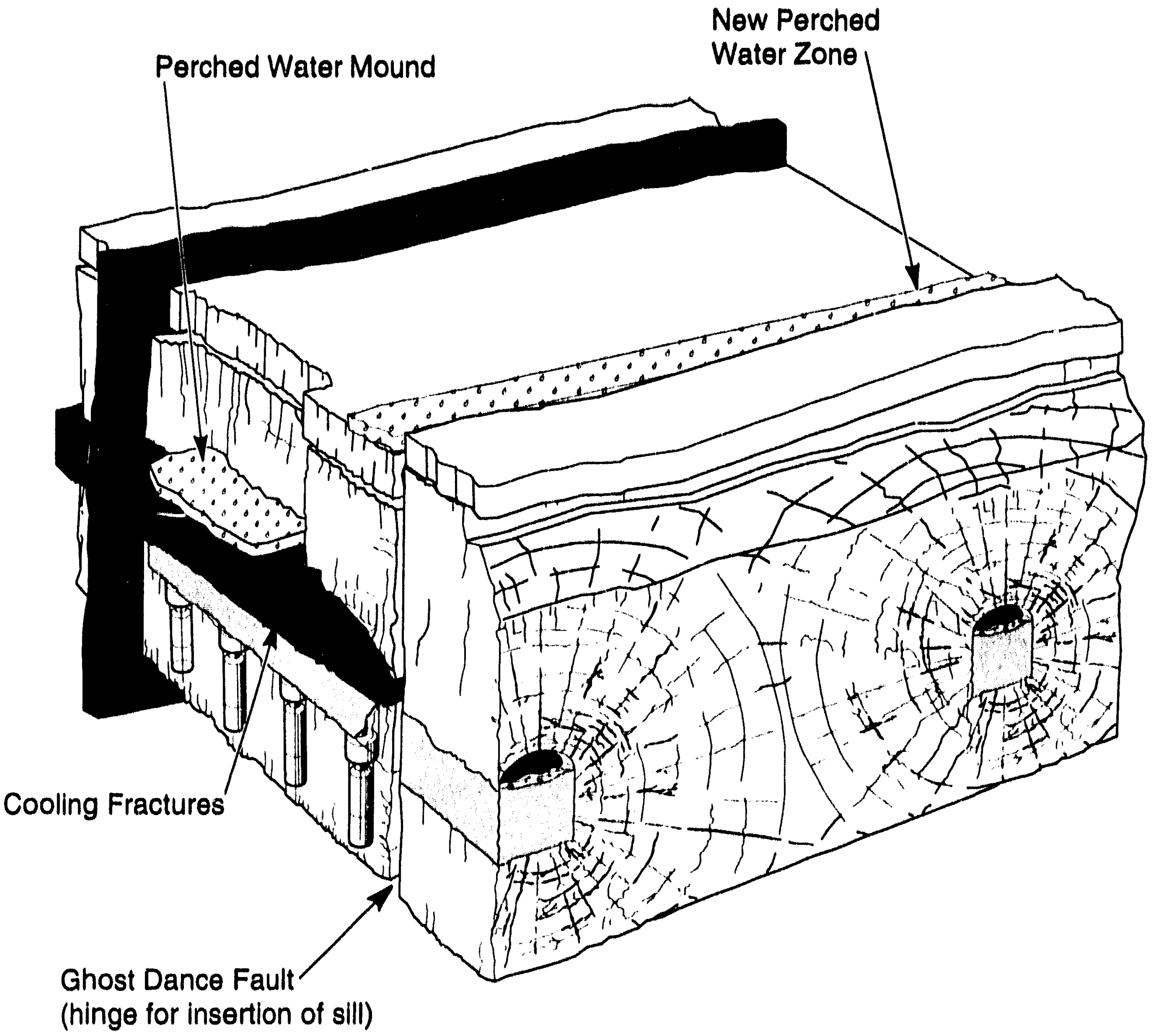
limited by the cooling fractures and by the permeability of the sill. Contaminants are distributed in the sill and subjected to both saturated and unsaturated mobilization processes. As indicated in the Sketch, contaminants can then be transported in locally saturated flow systems or in the unsaturated flow system. We again leave the distinction to the specifics of modeling. Our tree refers to a branch New Fractures Alter Hydraulic System in three separate Hydrothermal System Develops ζ_1 branches within Ⓖ. It appears that such fractures already need to be included in modeling of the convective flow system and in formation of perched water; further discussion would appear to be redundant. If experimental and field data suggest otherwise, we will reexamine the issue.

In the third sill model, suggested by a consultant (Dr. D. Borns, SNL), the presence of faults perpendicular to the direction of intrusion could allow hinging at the fault to accommodate the necessary uplift without obligatory creation of fractures perpendicular to the sill flow, as depicted in Sketch 12-7. The Ghost Dance fault has been picked as a specific example. In the discussion of effects of sill formation, Dr. Borns suggested that as the sill intrudes from the feeding dike, uplift is hinged at the nearby fault so that displacement can occur with little additional fracturing. The possibilities for waste/magma interaction associated with the bridging sill can still occur in this model.

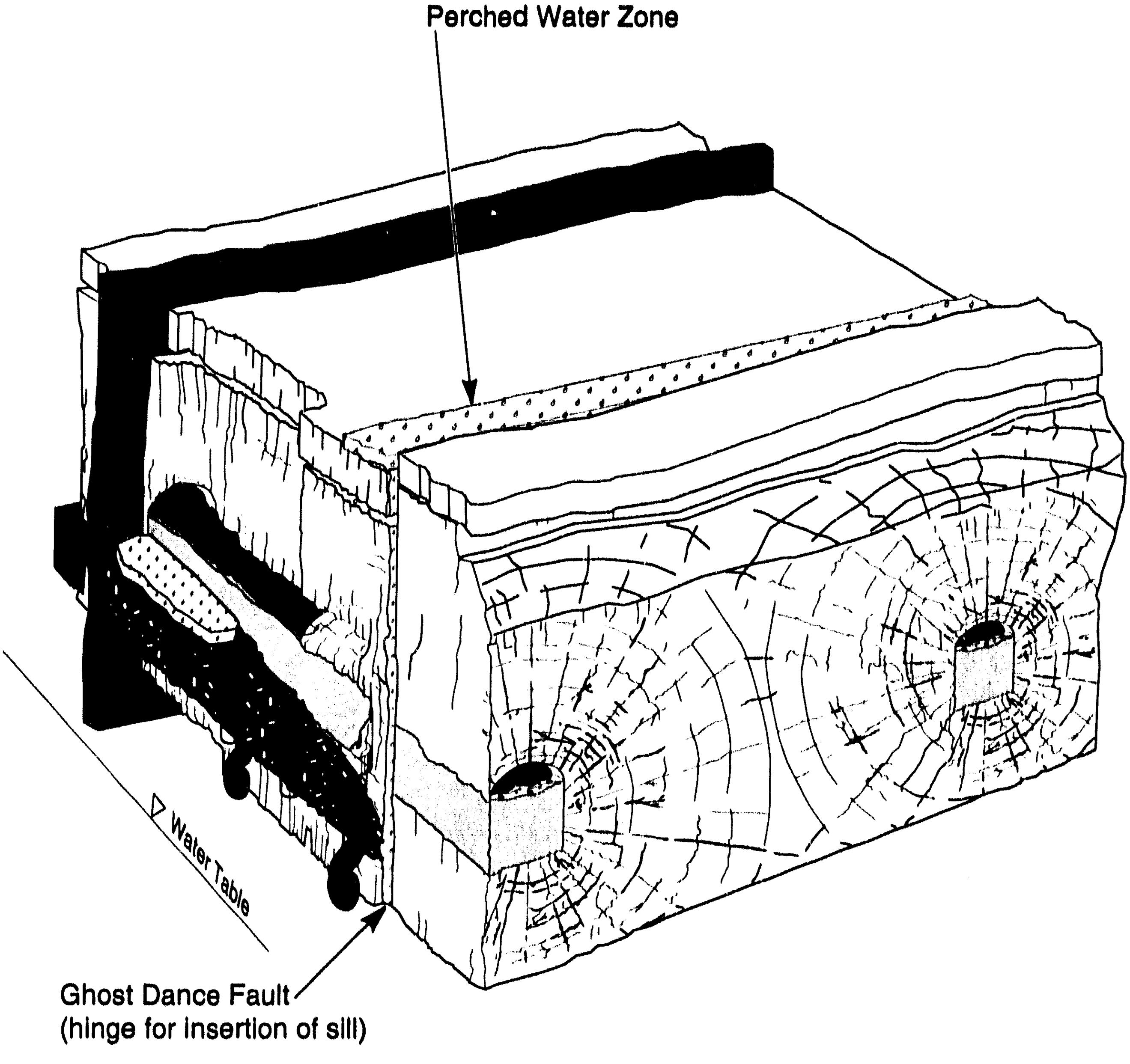
There are two differences from the scenarios developed for a tabular sill bridging between drifts without hinging. The first is that the systematic fracturing above the sill is probably much reduced, so alterations to the flow system, including the hydrothermal flow system, must be reconsidered. Second, movement along the hinge may alter the flow system down the fault, both above and below the potential repository. An example of such alteration effects on perched water is shown in Sketch 12-8. Essentially the scenarios produced here are identical to those produced under discussion of the tabular sill except for fluid flow directed by the hinge fault. Rather than repeat the earlier discussion, we will mention only 12-5, and indicate the changes by inclusion of Sketches 12-7, 12-8, and 12-9.



Sketch 12-7. Hinge model for a sill inserted in the vicinity of a fault requires no fracturing of the overburden. Overburden displacement is greater at the dike edge than at the hinge edge.



Sketch 12-8. A perched water system forms above the sill, mobilizing encapsulated waste into the flow system below the potential repository.

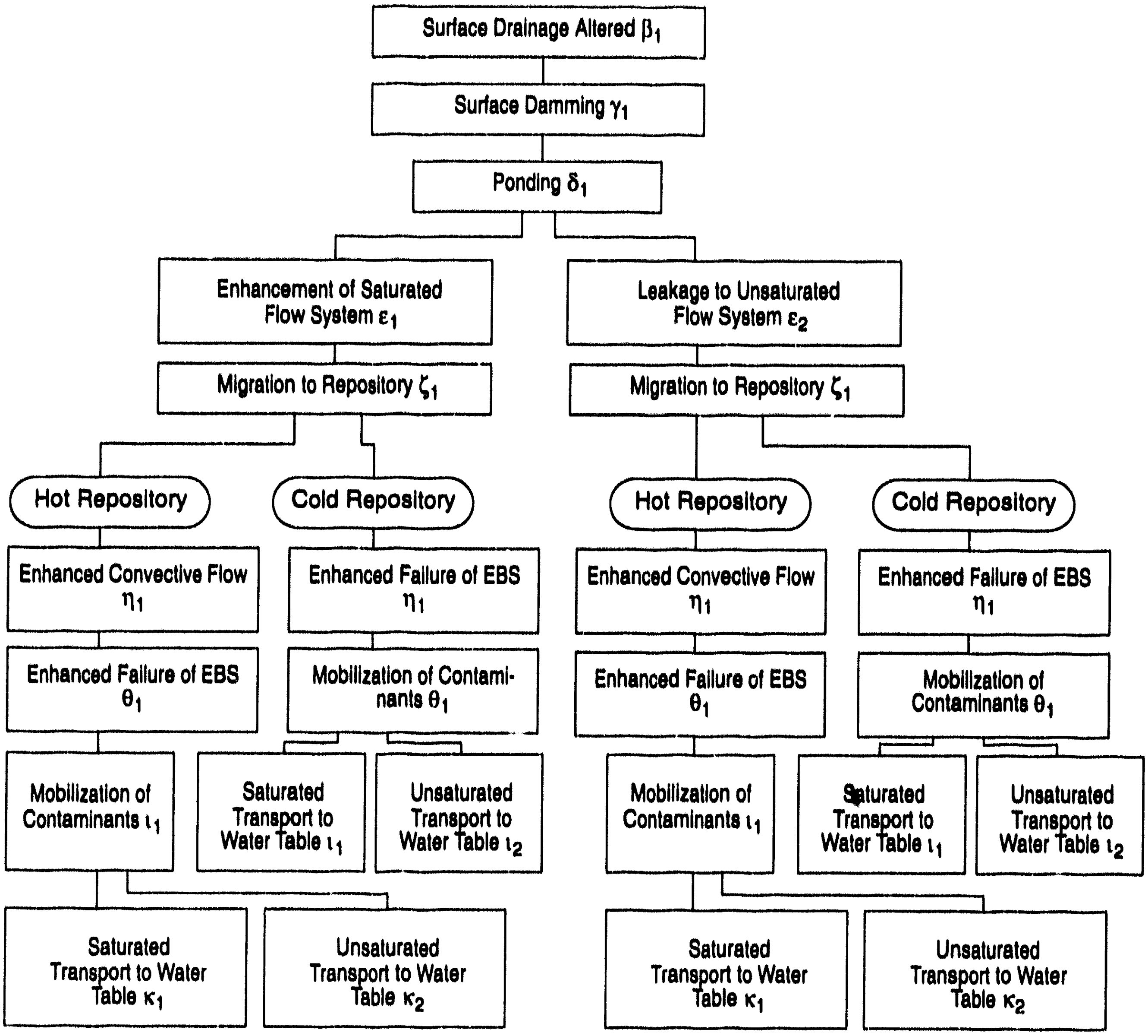


Sketch 12-9. Implications about saturated and unsaturated transport below the sill.

Intrusion Acts Indirectly on Repository (α_2)

In the α_2 branch of the event tree, we consider effects at the potential repository produced by an intrusion that does not intersect the potential repository. We expect that dikes and a cinder cone can alter the direction of flow and provide impoundment. That is, at the surface, dikes and a cinder cone can alter surface drainage, by redirecting flow and by damming washes, causing ponding. These effects alter local recharge. In the subsurface, one would also expect redirection of flow by damming (which would alter head and direction) or, in some cases, by providing more transmissive conduits for flow. In addition there are other possible effects. Intrusions could provide transient hydrothermal fluids and they could produce a reorganization of flow at depth, directing hotter fluids to the potential repository. The other possible effect is alteration of stress state at the potential repository because of emplacement of the intrusion and/or emplacement of the magmatic source.

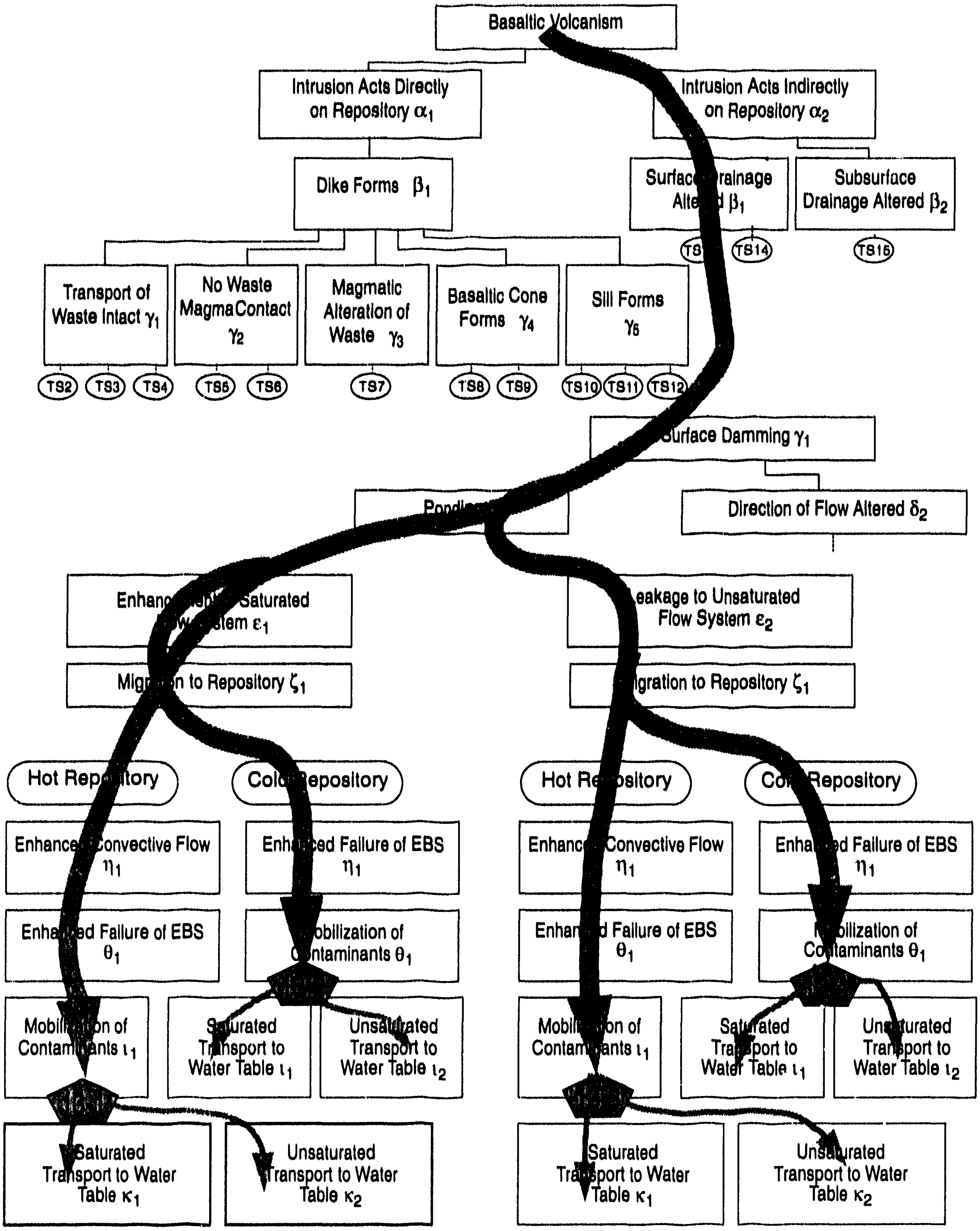
The actual consequences of intrusion on the saturated flow system depend on how the real system behaves. Currently we have several interpretations of the saturated zone, interpretations that will be resolved during site characterization. Scenarios constructed for this report reflect current alternative models of the flow system as we understand them now. We begin discussion of indirect action on a potential repository with the Ponding δ_1 branch of Alteration of Surface Drainage β_1 and Surface Damming γ_1 shown in (TS13)



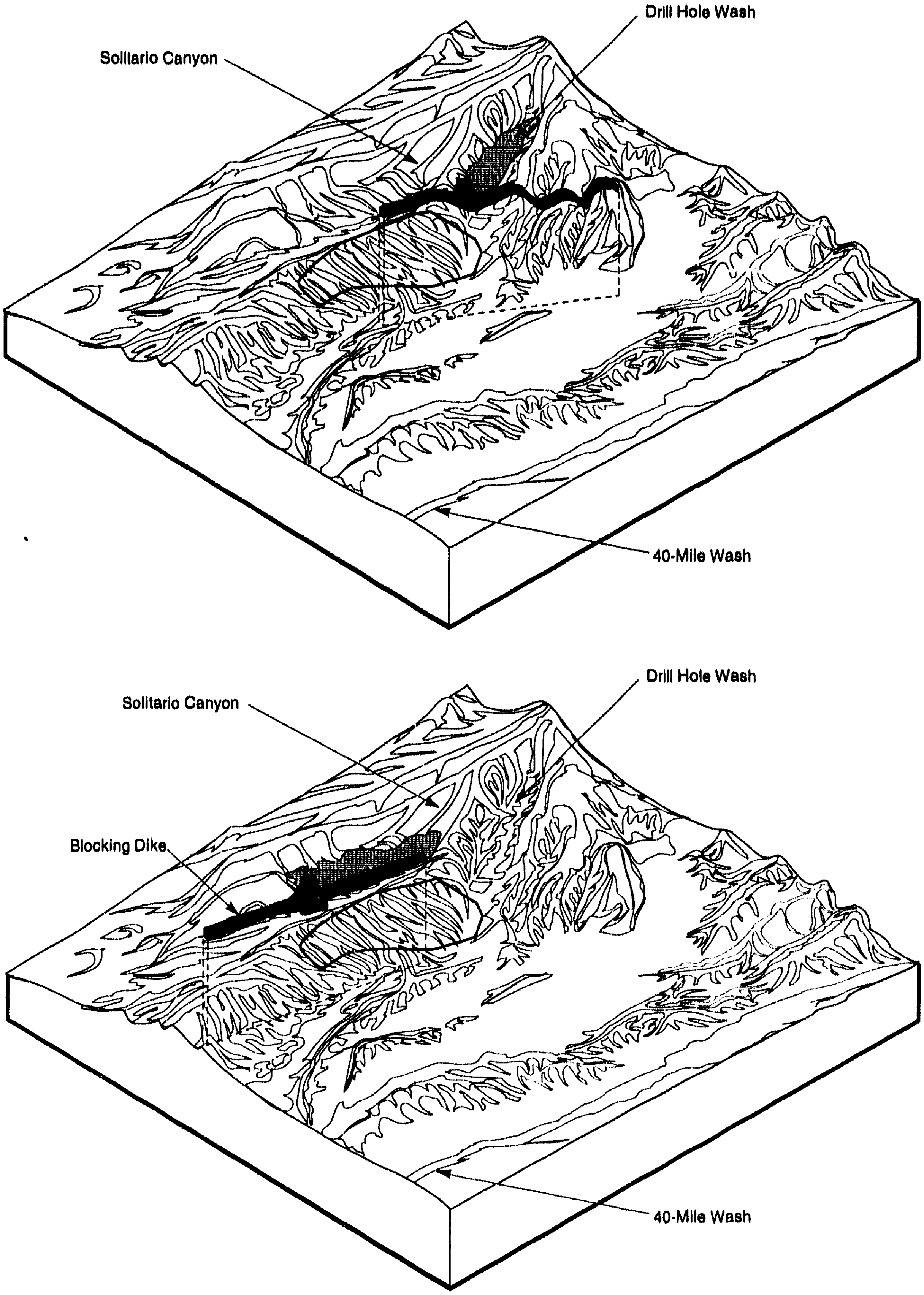
Tree Segment 13a. Basaltic volcanism, intrusion acts indirectly on repository α_2, surface drainage altered β_1, surface damming γ_1, ponding δ_1.

Surface Drainage Altered, Surface Damming, Ponding (TS13)

This part of our reference tree is seen in Tree Segment 13. Sketch 13-1 shows the occurrence of a dike and a cinder cone with lava flow at Drill Hole Wash, north of the potential repository along a trend perpendicular to the direction of least principal stress; and, similarly, a dike and cone in Solitario Canyon, west of the potential repository. For the following scenarios based on ponding, a cinder cone has grown just outside the wash and a lava flow has run down to block the wash, illustrating one example of how ejecta and lava flow might block the wash, producing ponding and possibly altering local recharge. Local recharge would be altered because ponding would give sufficient time for infiltration of fluids, which would



Tree Segment 13b. Scenario paths and scenario group paths of tree segment 13a.



Sketch 13-1. Dike and lava flow block drainage of Drill Hole Wash and Solitario Canyon.

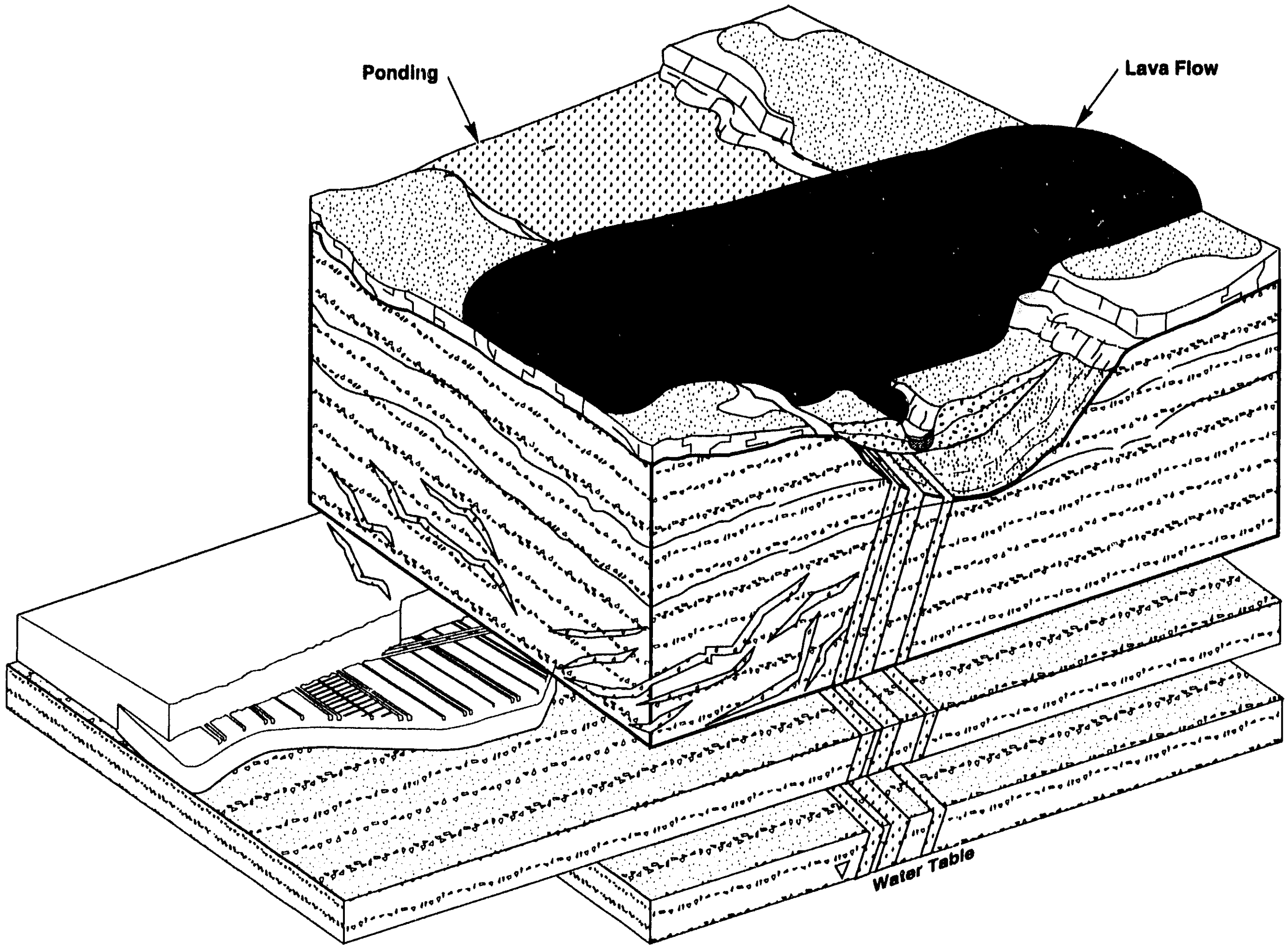
otherwise run further down the wash and be evaporated from the alluvium. An ash fall or scoria could be substituted for the lava flow. A mechanism is necessary to carry fluids from the pond to interaction with the potential repository. Leakage from the pond and presumably saturated alluvium beneath it could feed a locally saturated flow system in faults and fractures as in 13-1 and 13-2. Suggested details of this movement of fluids down the faults and through the fracture system are in Sketch 13-2. The same ponding could feed the unsaturated flow system, as with 13-3 and 13-4 and as suggested in Sketch 13-3. Both of these Sketches are drawn for a wash not over the potential repository, a circumstance that requires lateral migration to occur before a possible threat can be considered to exist. It is conceivable for the wash and pond to extend over the potential repository if the dam (dike, lava flow, or cinder cone) doesn't extend over the potential repository. We will leave this as a special case for modeling.

For these cases of indirect effects, the thermal output of the dike has for most purposes been removed from the problem. As mentioned in the introduction, we have presumed that the thermal output of the potential repository established the initial conditions at the time of the intrusion but that thermal effects were dominated by the hot dike. When modeling is more advanced, we will know whether this presumption suffices or whether separate scenarios are needed for the cases of hot and cold repository. In the case of a more remote intrusion, however, the thermal output of the potential repository is important. It will determine how these additional fluids reach waste. In further expansion of the tree, these effects need to be added. This is done by distinguishing between a Hot Repository and a Cold Repository.

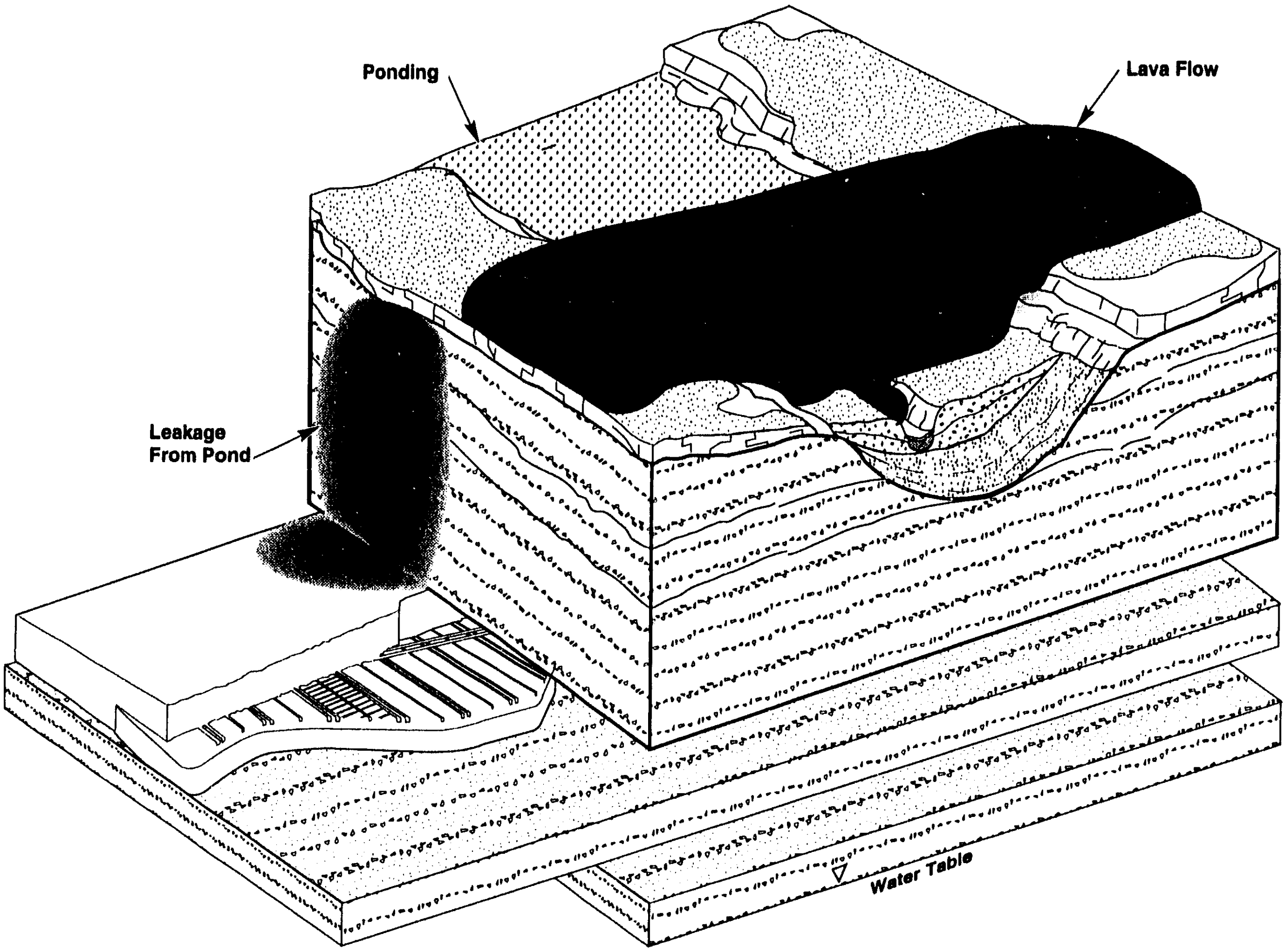
A Hot Repository we defined for these considerations as one whose thermal output from containers is sufficient to produce two-phase convective flow substantially greater than that caused by the geothermal gradient. Path 13-1 includes ponding with saturated flow to a hot repository. We have chosen not to distinguish between saturated transport and unsaturated transport in the text, but rather to say that once additional fluids are available to the EBS, containers, and waste, the mobilization and transport modes discussed in the Tree Segments 2 through 6 would apply. Detailed thermal modeling will have to be done to realistically estimate how fluid will circulate around the hot repository.

The heat-producing period, as currently planned, is only a small fraction of the potential repository lifetime. The cold repository is exposed to the possibility of a saturated flow system conveying fluid from the surface pond. This occurs basically over the normal geogradient in temperature, so temperature is only a weakly coupled dependent variable. These fluids could continue down fractures to the waste container, essentially providing a saturated bath for interaction with the container and waste similar to the processes for this interaction in (TS4). A possible alternative is that a fracture leading to the waste dead-ends but that fluids leak from the fracture into the rock matrix to form an unsaturated plume continuing to the container. This also is a previously discussed process that is illustrated in (TS4) Sketch 4-5. The process includes contaminant movement in a plume and in fingers fed by the unsaturated plume, thus completing the discussion of 13-2.

Path 13-3 considers leakage from the pond to the unsaturated flow system above the water table as Sketch 13-3, which shows the movement of an unsaturated plume flowing near enough to the potential repository to interact with the heat generated by the waste. Although the vapor phase can interact strongly with the container and waste, only volatiles can be transported until liquid water in the form of the unsaturated plume or the condensate can



Sketch 13-2. Impounded water leaks into a locally saturated zone consisting of faults and fractures extending laterally to the potential repository.

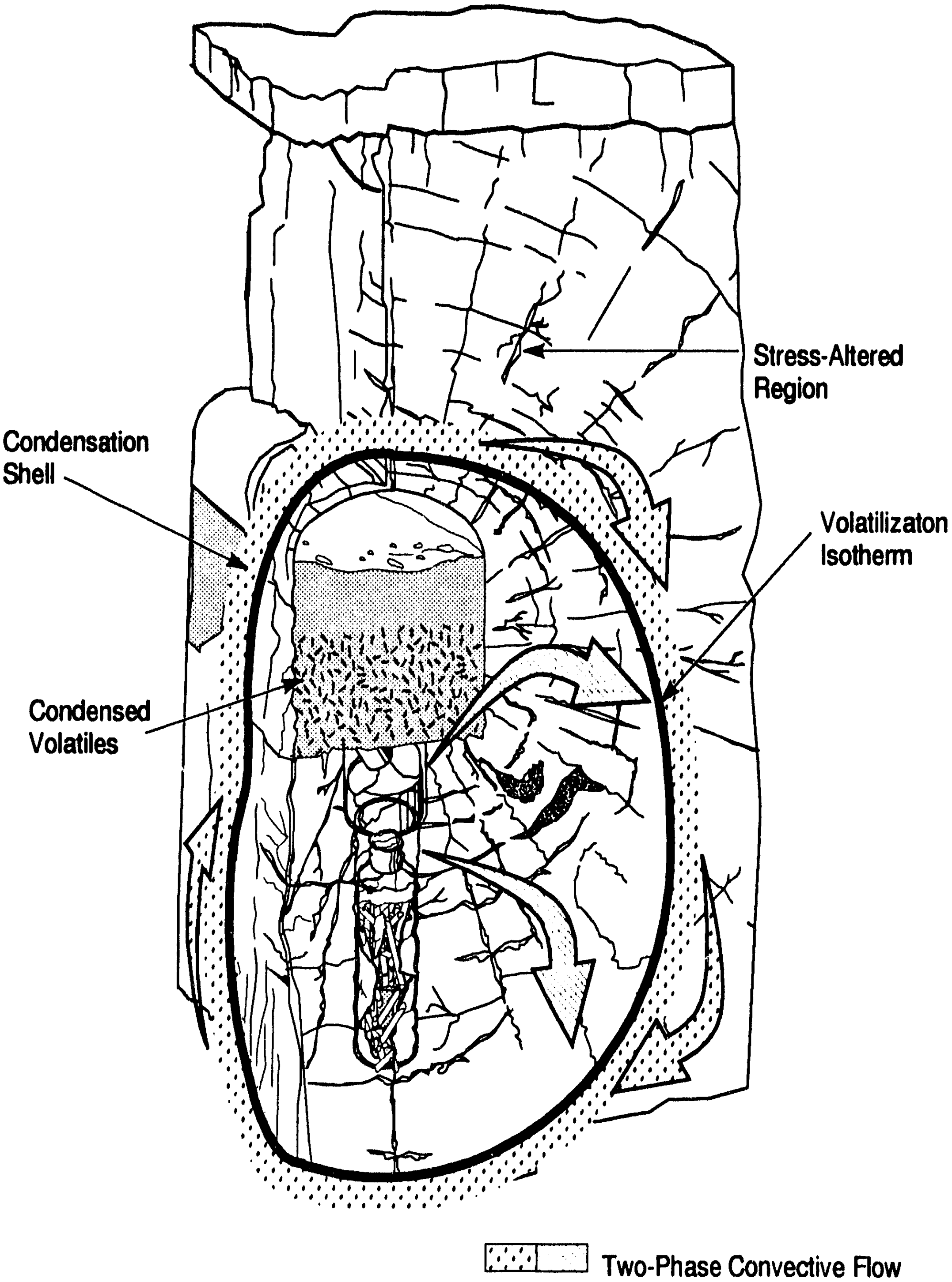


Sketch 13-3. Leakage of impounded water into the unsaturated zone, enhancing flow to the potential repository.

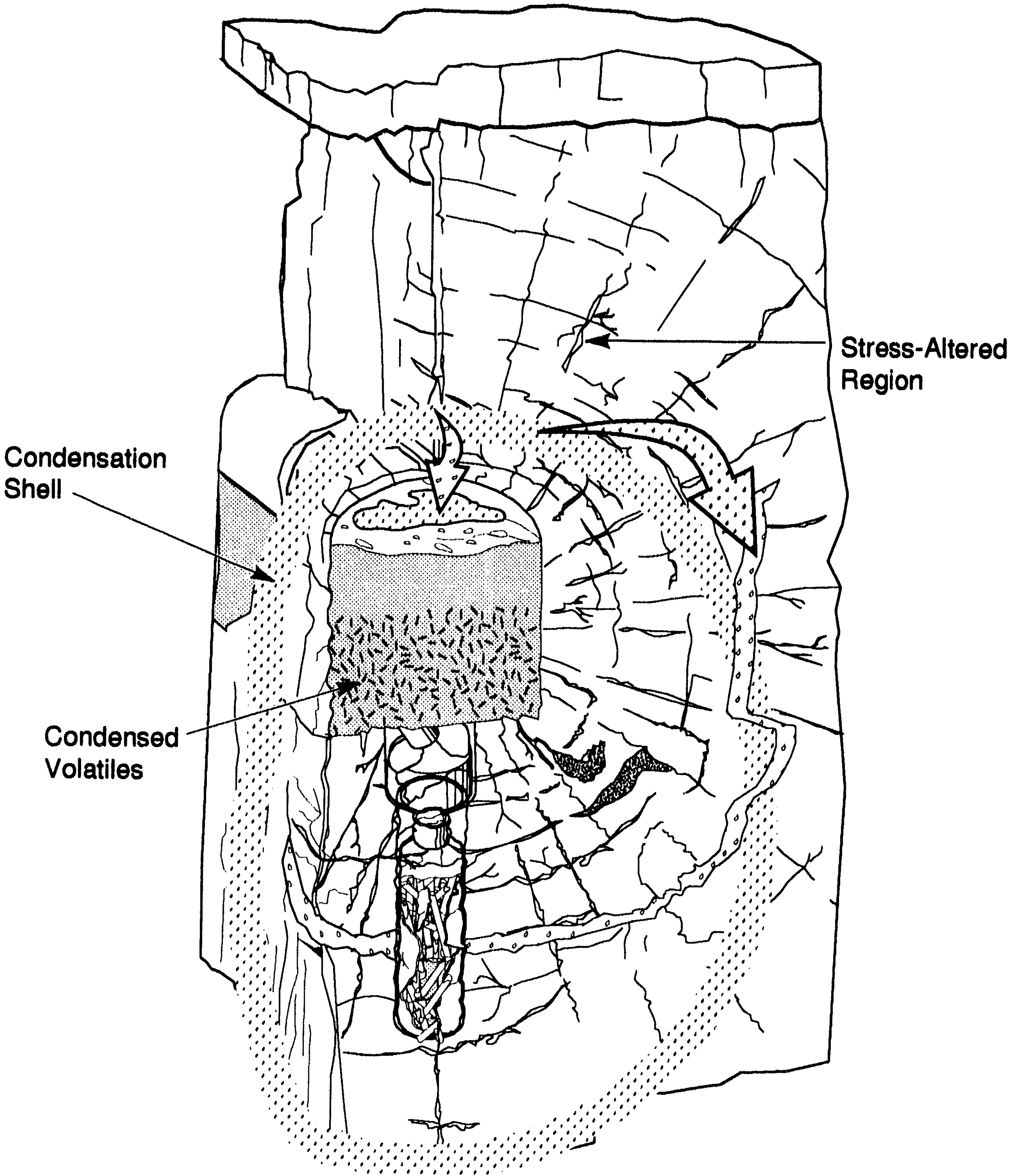
reach the waste. Therefore, processes described as mobilization and transport occur when temperature allows liquid water to return to a container. An extreme example of the return of liquid water is that of reflux from a condensation shell (Sketches 13-4 and 13-5), which would form outside and above the vaporization isotherm (and presumably around it as well). This condensed water vapor (now liquid) would be greater in volume than otherwise because of the supply from the recharge from ponding. Gravity and capillarity would then bring part of this fluid to the containers. Because heat production is a continuous process, conduction and convection are also continuous--there is no off/on switch on fluid reflux from the condensation shell. Therefore, exactly how the process behaves needs more investigation.

We still have in 13-4 the possibility that the leakage from ponding occurs when the potential repository is cold, as it will be for most of the regulatory period. Ponding would add fluid to the unsaturated flow system, enhancing flow to and past the waste. If increased flow implies enhanced failure of the EBS, we would expect more rapid release.

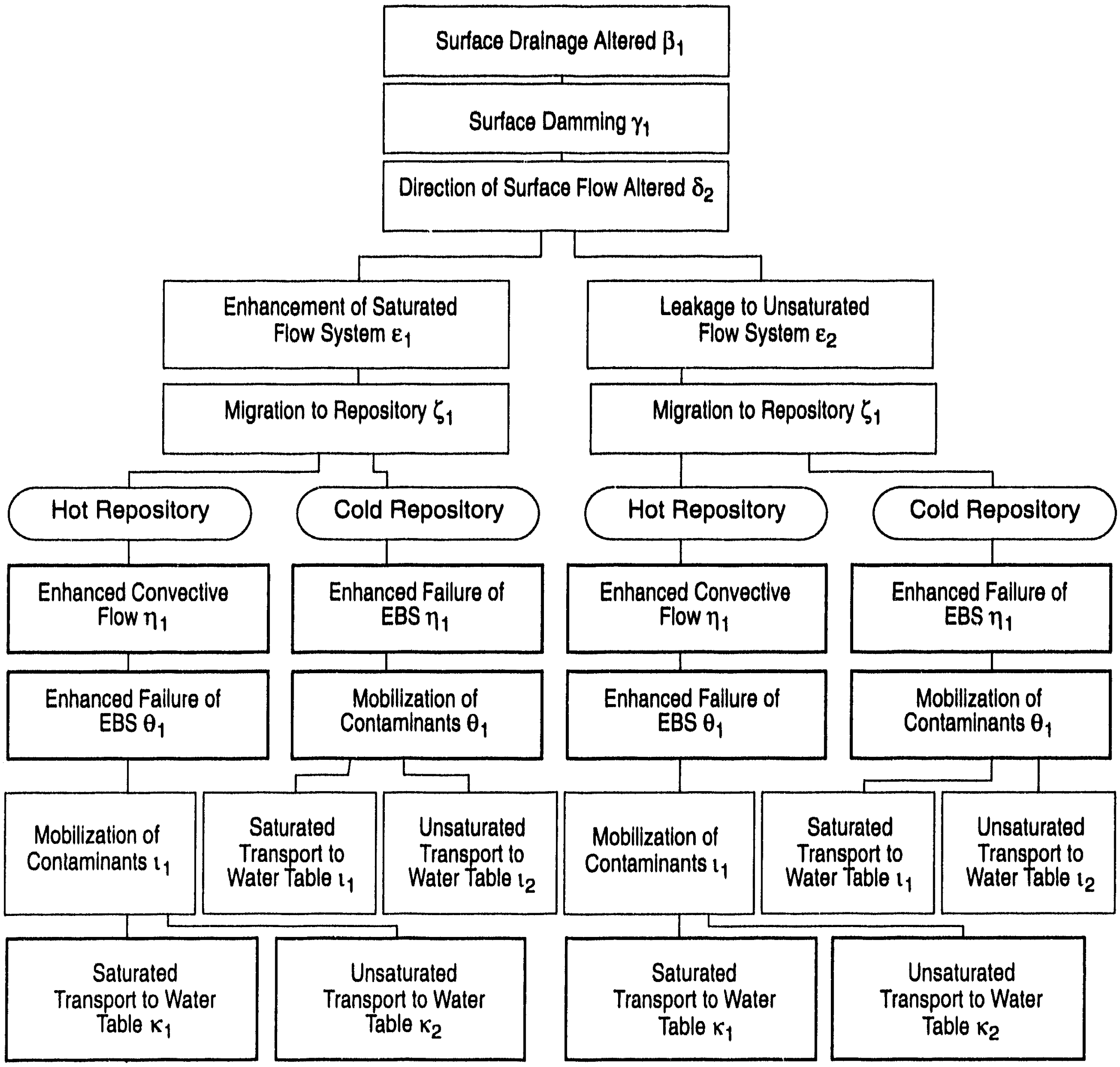
As stated before, mobilization and unsaturated transport are represented in previous discussions. We recognize a general unsaturated transport and the possibility of fingering in this process. It is possible, because of property changes in the rock, for some locally saturated flow to occur in the composite-model sense and in the sense of fracture flow. We have not shown this; it is a detail of modeling that we presume will be implicit in the code calculations. We simply identify the saturated extension, Saturated Transport to Water Table ι_1, of 13-4.



Sketch 13-4. Condensation shell forms outside the volatilization isotherm during the hot period of the repository.



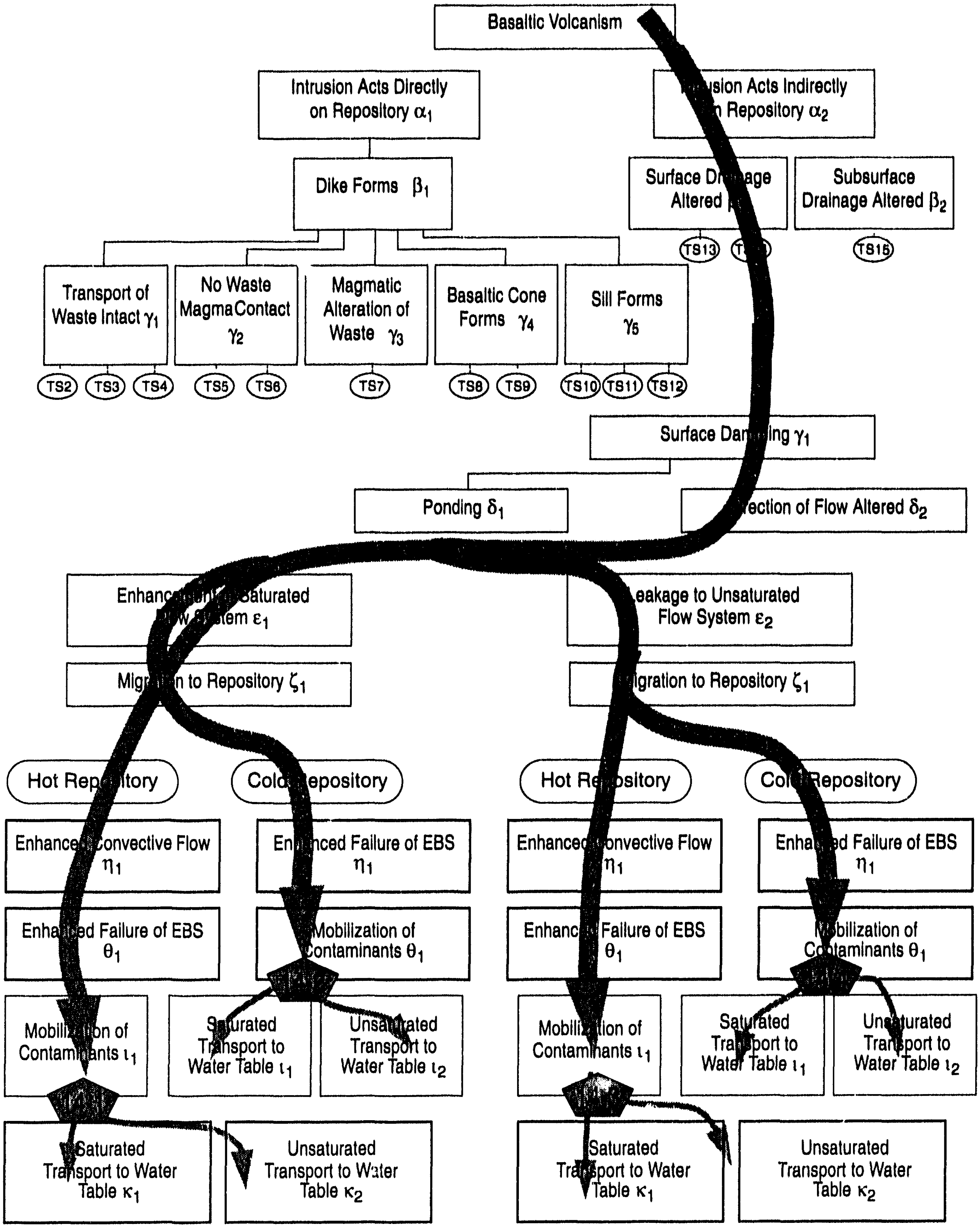
Sketch 13-5. Water from the condensation shell finds pathways to contaminants as the potential repository cools.



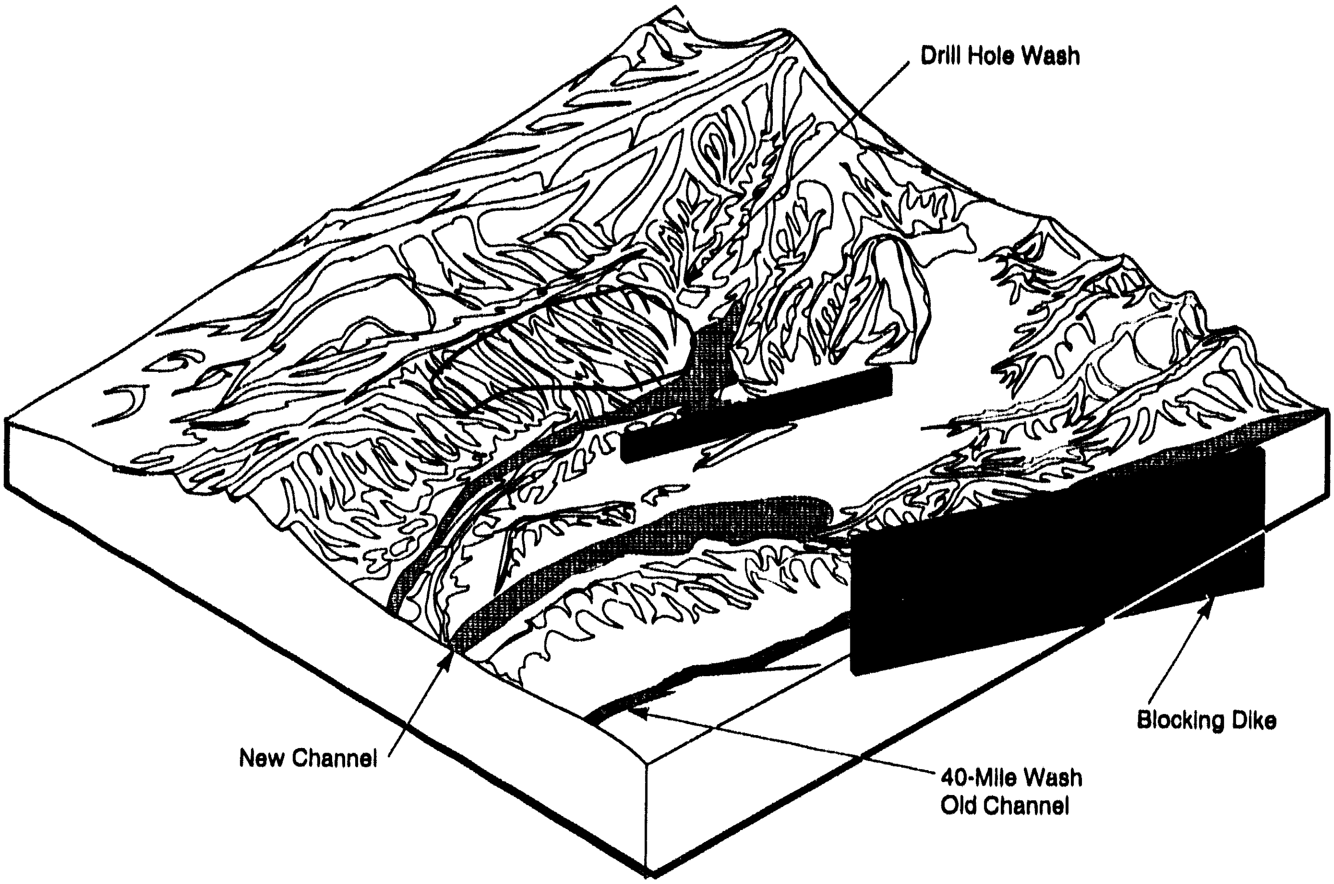
Tree Segment 14a. Basaltic volcanism, intrusion acts indirectly on repository α_2, surface drainage altered β_1, surface damming γ_1, direction of surface flow altered δ_2.

Surface Drainage Altered, Surface Damming, Direction of Flow Altered (TS14)

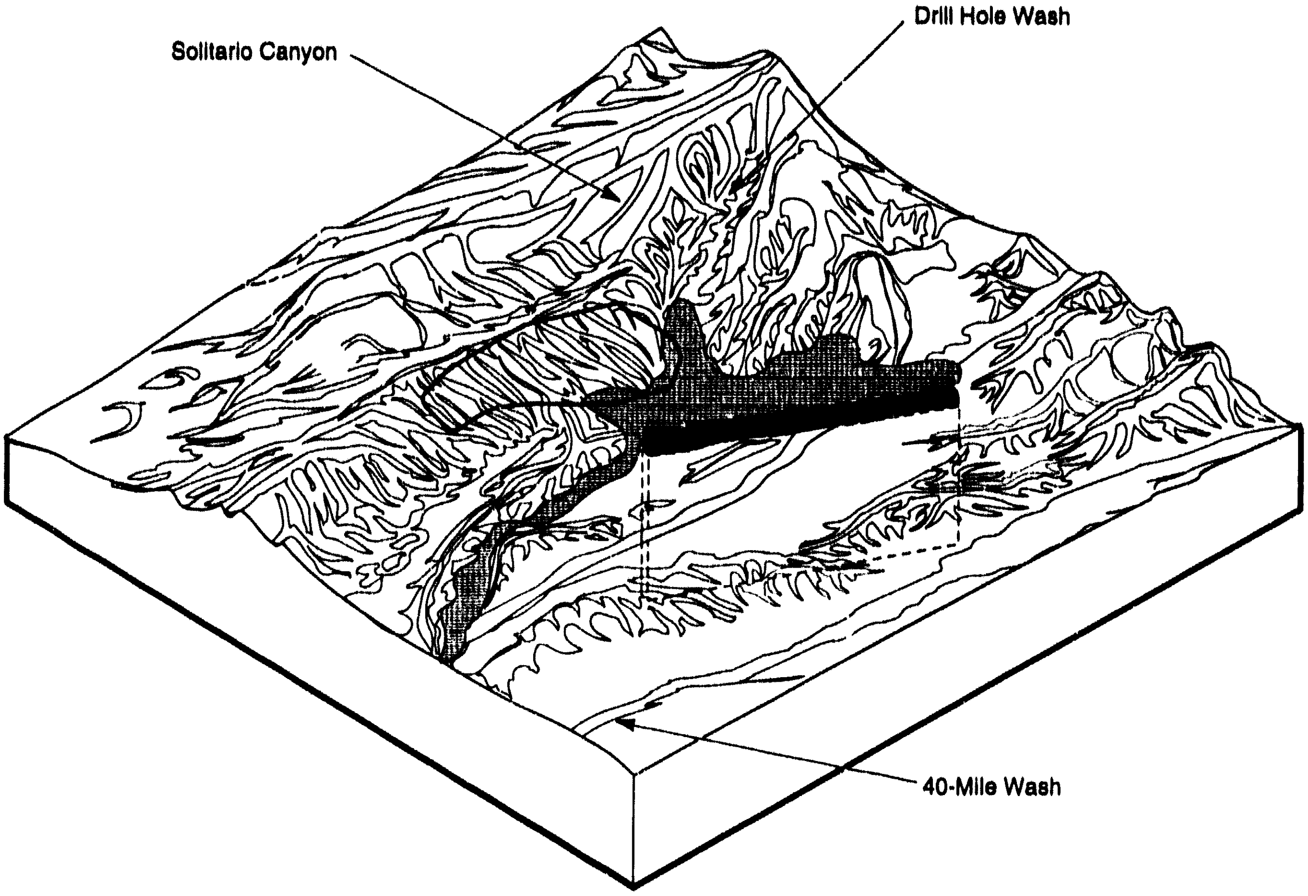
In addition to ponding as a consequence of surface damming, the direction of surface flow (and subsurface infiltration) could be altered. Examples of this are blockage across Forty-Mile Wash so that the wash is forced to migrate westward and cut a new channel closer to the potential repository, and blockage across the extension of Drill Hole Wash in Midway Valley that produces a similar migration. Both of these examples are illustrated in Sketch 14-1. No new direct connection to the potential repository is postulated, so continuation of the Tree Segment 14 mimics the branch below ponding. Namely, there may be leakage (infiltration)



Tree Segment 14b. Scenario paths and scenario group paths of tree segment 14a.

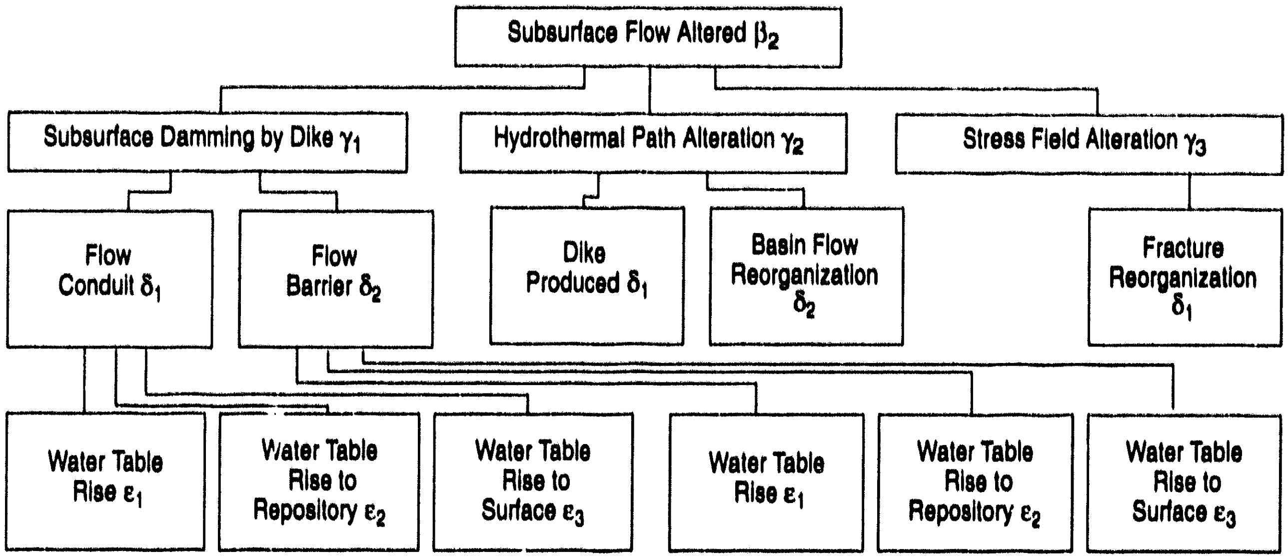


Sketch 14-1. Dikes blocks drainage from Drill Hole Wash or Forty-Mile Wash.



Sketch 14-2. Dike causes flow channel to migrate closer to potential repository.

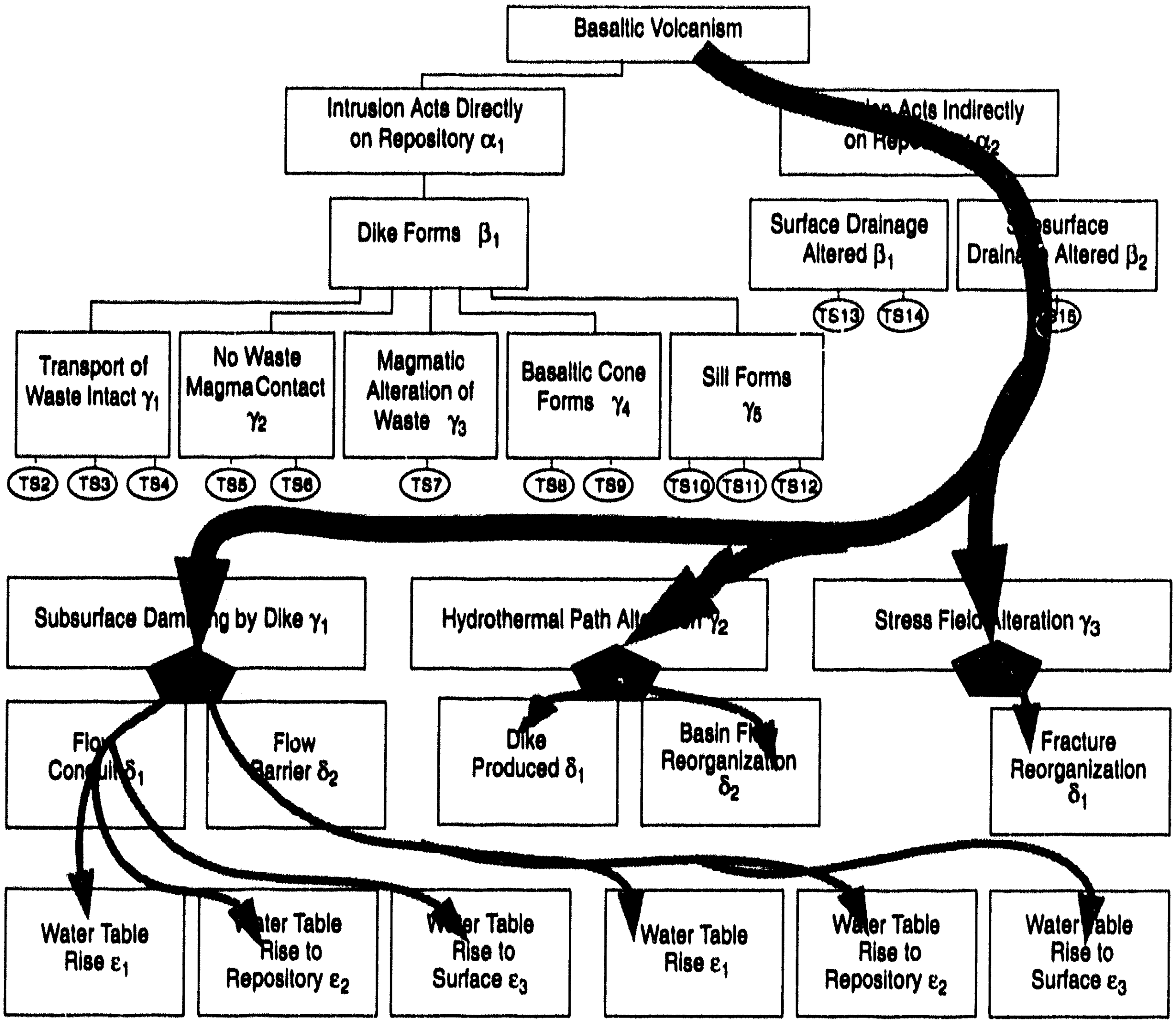
to the unsaturated flow system and enhanced saturated flow. In both cases, there must be some lateral migration to the potential repository. As seen in Sketch 14-2, the redirection of flow causes migration of wash channels, followed by the processes of (TS13) that carry fluid to the containers either in a saturated or in an unsaturated mode. The ensuing branches are replicas of the corresponding branches of (TS13) under ponding, fed by infiltration from the new channel location rather than the pond.



Tree Segment 15a. Basaltic volcanism, intrusion acts indirectly on potential repository α_2, subsurface flow altered β_2.

Subsurface Flow Altered TS15

This brings us to **Tree Segment 15** and the issue of **Subsurface Drainage Altered β_2**, which includes those effects that alter the subsurface flow system. So far we have identified alteration of the saturated flow by the physical presence of a dike, by changes in the local stress field produced by the intrusion, and by readjustment of hydrothermal flow caused by the intrusion. We begin this discussion with the branch **Subsurface Damming by Dike γ_1**. **Sketch 15-1** illustrates the idea of dike intrusion relative to the potential repository. These figures have current, undisturbed head contours (as they are presently interpreted) superimposed on the potential repository and surroundings. Calculations, with dikes inserted, produce substantially altered heads and flow directions, depending on the hydraulic properties assumed for the dikes and are the reason for inclusion of these features. This is a water-table aquifer, so these contours represent elevation above mean sea level. Inserting dikes in the sample locations of the model paradigm would be expected to change the water table at the potential repository. The actual effects depend on the correct description of the flow system. There are a number of alternative models of the flow system (Czarnecki, 1985; Sinton, 1989; Fridrich et al., 1991). Which model is actually representative, a matter to be determined by site characterization, has a profound effect on the residence time of water in the saturated zone beneath the potential repository and on flow directions. If, for example, the correct interpretation of the saturated flow field is one of more or less continuously varying hydraulic conductivity, so that conductivity contrasts are the cause of the head variation from north to south (including the high gradient at the north), then emplacement of a low-permeability dike as in position 1 would produce a dam. Such a structure would redirect flow south and cause a water table rise at the potential repository. If, on the other hand, the dikes in position 1 are highly transmissive, they might act as conduits channeling flow around the potential repository. The cause of the high gradient north of the potential

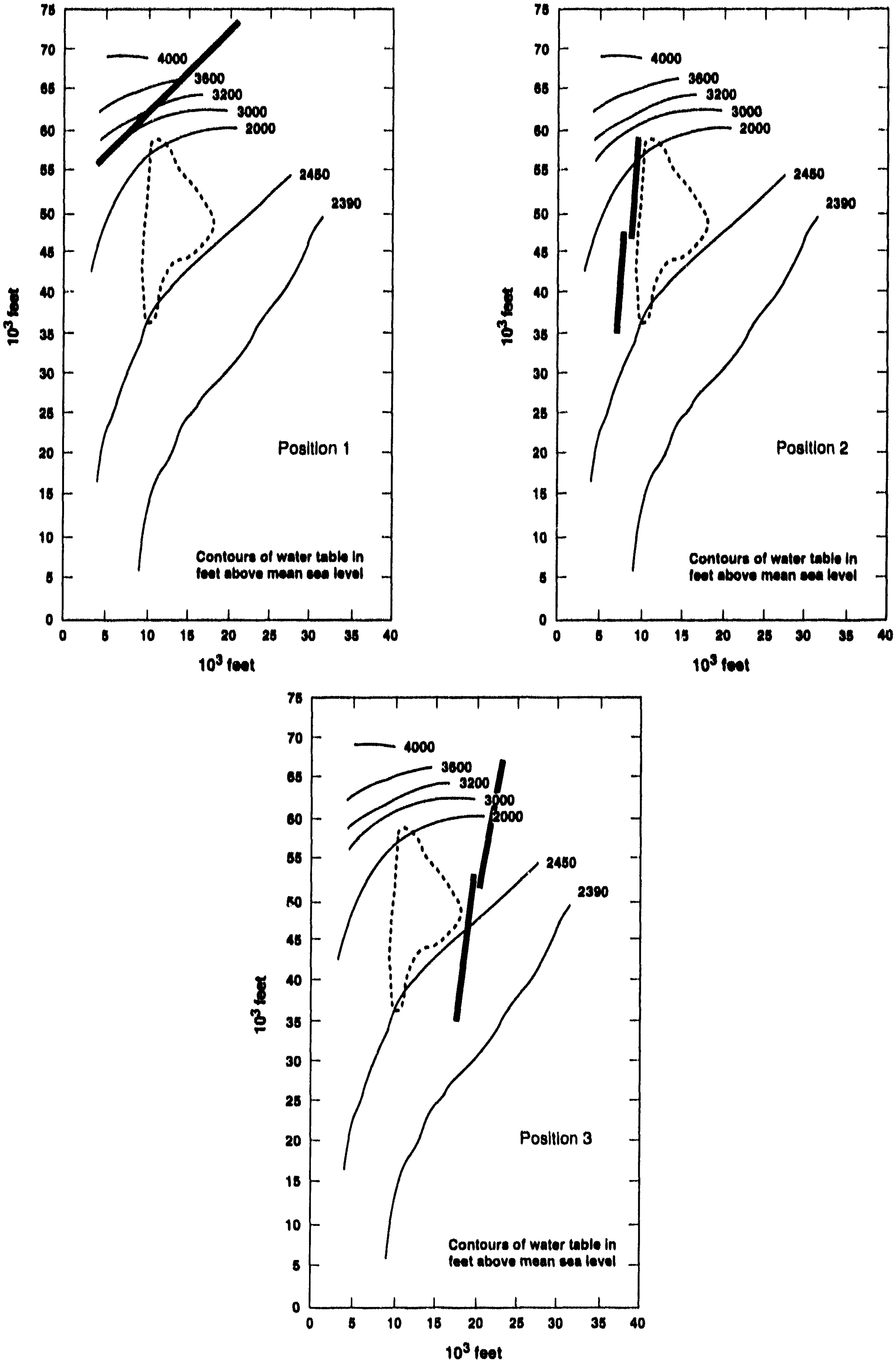


Tree Segment 15b. Scenario paths and scenario group paths for tree segment 15a.

repository is a matter of conjecture and concern. Fridrich et al. have proposed an interpretation that depends on the location of the subcrop of the Eleana formation and a connection between the water-table aquifer and the carbonates underlying that region. Water is diverted to flow below the potential repository before upwelling back to the water table aquifer. Position 2 is directed at this interpretation. The dike is placed to interfere with this specific flow system so that there could be major rise to the water table.

The point of this discussion is that while we can and will speculate on gross features of dike emplacement, speculations on the details of interactions, even on the level of earlier discussions, are not possible without careful characterization of the saturated flow system.

Tree Segment 15b is short: both Flow Conduit δ_1 and Flow Barrier δ_2 have the same subbranches. What one suspects is that early after emplacement the dike represents a flow barrier and then

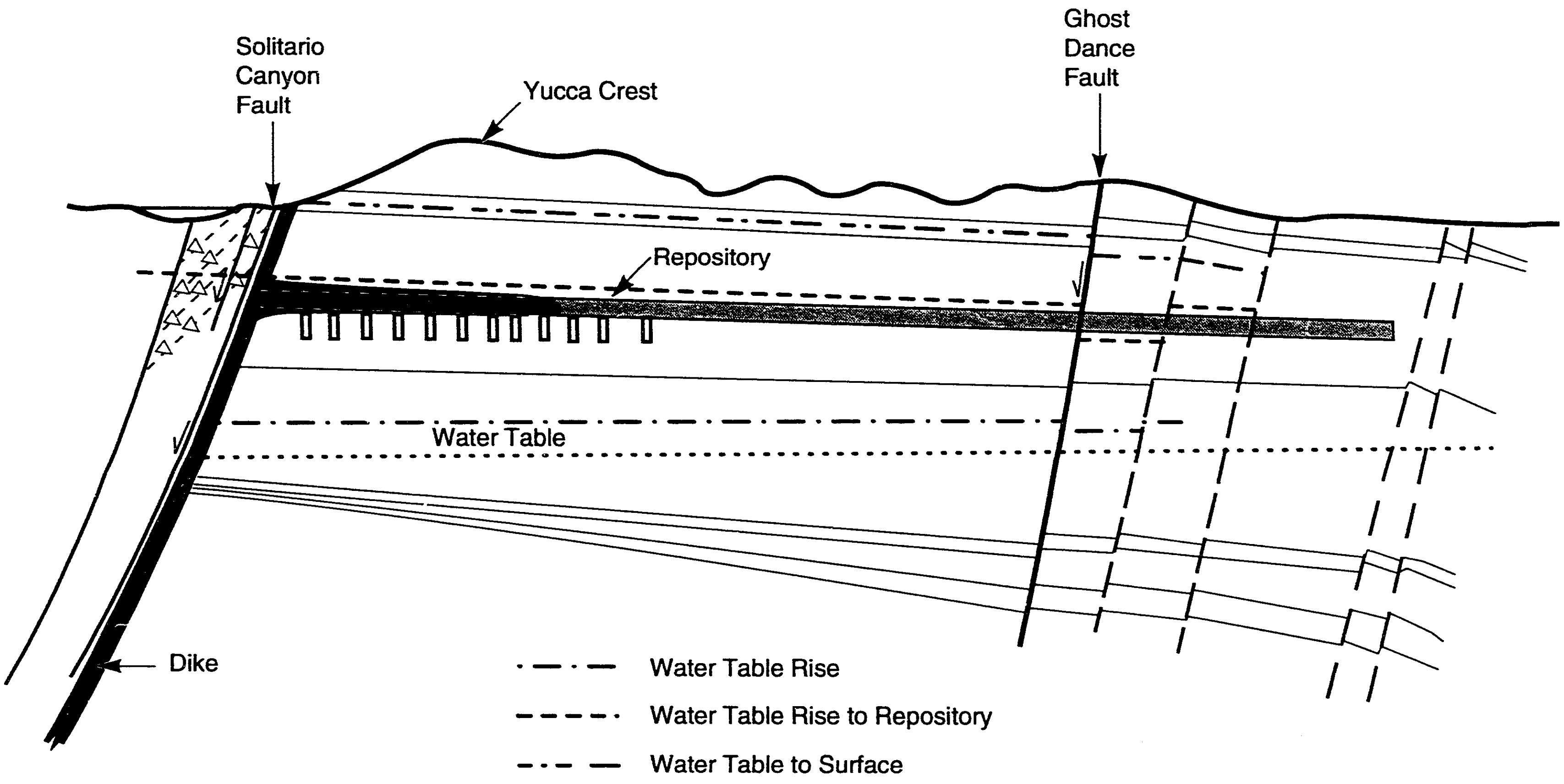


Sketch 15-1. Three hypothetical dike locations superimposed on extrapolated head contours in the region of the potential repository.

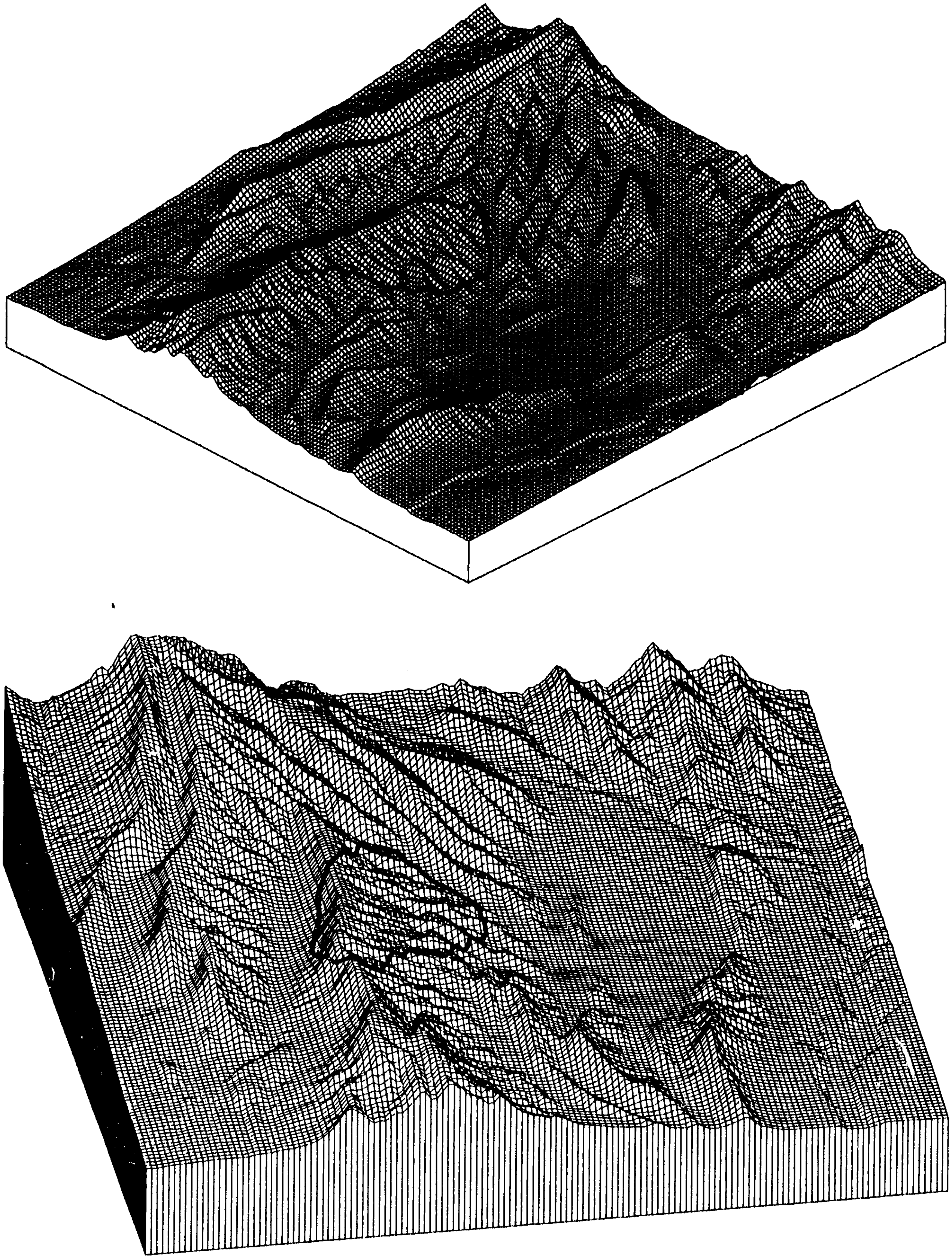
gradually changes to be a fairly well-fractured flow conduit. Both circumstances allow the possibility of Sketch 15-2: a water table rise, a water table rise to the potential repository, or to a surface outfall. Sketch 15-3 illustrates the topography of Yucca Mountain and vicinity from two different views. There is enough surface relief so a sufficient water table rise could have places to produce springs and seeps. Sketch 15-3 is included to give some perspective to the scale of water table rise required to reach the potential repository and to reach the land surface. The best we can do for these scenarios is to identify 15-1 and plan to revise and expand this branch when the saturated flow system is better defined.

This leaves two interesting but even more speculative branches of Subsurface Flow Altered β_2. The idea behind 15-2, Hydrothermal Path Alteration γ_2, is that the intrusion, in penetrating the carbonates on its way to the tuff water table aquifer, interferes with the flow path of deeper waters. Whether the dike provides a barrier or a conduit, the net result is that the deeper flow system is reorganized and warmer, deeper waters are directed into and circulate in the tuff aquifer. Since regional springs are known at about 40 °C, the temperature change in the tuff aquifer could be significant. Even if the flow path of the warmer mixture does not reach the potential repository, thermal expansion of the water could raise the water table. In order to pursue these ideas more than superficially, we need many more details of the flow system at depth and the possible interactions of those systems with intrusions. As a better understanding of the regional flow at depth becomes possible, we will reexamine these ideas in order to identify specific scenarios. At present we will leave this topic as an open issue.

15-3, containing Stress Field Alteration γ_3, is based on another very interesting idea. It depends on the observation that emplacement of an intrusion (a dike or magma body) strains the country rock. That strain must be accounted for somewhere in the system. Some part is elastic and some part is permanent deformation. That deformation could be taken up in part by readjustment along fractures in Yucca Mountain. If fracture transmissivity is reorganized when strain is accommodated, then how fluids enter and move through the mountain may change. To provide more than trivial scenarios we need more details of how strain is taken up in the near surface (and deeper) and the amount of strain that needs to be accounted for. There undoubtedly is an interesting scenario to be developed here, but at present we do not know how to proceed.



Sketch 15-2. Cross section of Yucca Mountain showing the water table for the three branches of this Tree Segment.



Sketch 15-3. Topography of Yucca Mountain from two oblique views.

Open Issues

The probability of occurrence of basaltic igneous activity in the Yucca Mountain area is presently thought to be sufficiently low (Crowe et al., 1982; Ho, 1991) that examination of the details in many scenarios which were just constructed seems unnecessary. If new estimates substantially increase that probability or if regulatory authority decides to reduce the limits of what must be considered, then the details of the interactions developed here will need to be examined. We have identified a number of such details, which we left as open issues in the text, and they are summarized here. These issues appear to be of three types: those involving the mechanics of igneous activity, those involving interaction of magma with the waste containers, and those involving alteration of the flow system.

Mechanics of Igneous Activity

a) Injection of Dike/Sill in a Stress-Altered Region (page 2)
b) Polycyclic Nature of Eruptions (page 81)
c) Plumbing of the Cinder Cone (page 81)

Magmatic interaction with Containers

d) Magmatic Entrainment of Spent Fuel (pages 10 and 17)
e) Condition of the Waste (pages 10 and 14)
f) Seismic Damage to Containers (page 14)
g) Container Survival in Magmatic Volatiles (page 65)
h) Magmatic Alteration of Waste (page 71)

Hydrologic Behavior of Intrusions

i) Fracture Development in Dikes (page 135)
j) Fracture Development in Sills (page 107 Ⓕ)

These issues will be discussed briefly individually in order to indicate the questions involved.

Issue a Injection of a dike or sill in a stress-altered region. If a dike injected through the potential repository intersects any emplacement drifts, it has intersected a region different from the surrounding country rock. Repository drifts, even if backfilled, form a void space to be intercepted by the magma flow. In addition, drifts are surrounded by a stress-altered region extending out to perhaps six drift radii. Radial and concentric fractures form to relieve the stress. Drifts themselves occupy perhaps 20% or less of the potential repository plan view. An intruding dike, kilometers in length, rising from many kilometers, sees these stress-altered zones and drifts as windows occupying a small percentage of its vertical aspect. We do not know how a dike reacts to the stress-altered region and to the void space. Are these openings too insignificant to matter, or do they bias intrusion of the dike? The void spaces of the drift could allow greater vesiculation of volatiles in the dike; that is, gas comes out of solution at the drifts rather than closer to the surface. The importance of these voids as a gas reservoir is expected to depend on the rate of exsolution from the magma and possibly on the flow of magma into the drifts. The eventual gas confining pressure is then the overburden pressure at the potential repository. Does this same stress-altered region favor formation of sills? If so, is there a preferred location at the drifts, at the outer limits of stress-alteration?

Issue b Polycyclic nature of eruptions. The Lathrop Wells cinder cone has been interpreted as being produced by several eruptions (Wells et al., 1990), well-spaced in time. If a cinder cone is polycyclic, is the original vent reused or is there some movement of the vent? Does the vent movement occur above or below potential repository level? Are repeated cycles associated only with vent use or are new dikes emplaced as well?

Issue c Plumbing of the Cinder Cone. At the end of an eruption cycle there is a main vent and possibly satellite vents. During the eruption does the vent wander (change location) at the level of the potential repository? At what depth do satellite vents develop? Does the vent grow at potential repository depth during reuse? All these concerns about the plumbing system for the cinder cone are directed at forming a basis to estimate the number of containers actually at risk.

Issue d Magmatic entrainment of spent fuel. A dike intersecting containers could entrain pieces of waste, e.g., spent fuel fragments, and carry them to the surface. Similarly, flow up a vent can entrain fragments and disperse them. While glassified waste may be similar to the country rock, spent-fuel pellets are substantially denser. It is unclear that spent-fuel pellets can actually be carried to the surface. The question is the following: under what circumstances (velocity and density of magma, size of particles, etc.) can waste be carried to the surface in a dike and in a cinder cone vent?

Issue e Condition of the waste. What is the physical condition of the waste? If it is spent-fuel, does high-burnup reduce the integrity of fuel pellets? If it is glass, do cooling, shipping, and emplacing produce substantial fracturing? When are these physical alterations important for interaction with the magma?

Issue f Seismic damage to waste containers. During the course of this igneous activity, one would expect an almost continuous pattern of small seismic events, perhaps lasting for months. Are these seismic events capable of causing damage to containers or their contents, whether spent-fuel or glass?

Issue g Container survival in magmatic volatiles. The intruding magma exsolves volatiles as it moves and cools. These volatiles often form aggressive fluids--fluids that may be quite hostile to the waste containers. Such behavior is known from field experiments at volcanic vents and fumaroles. We need to have a reasonable idea of what fluids containers might see and what volumes of such fluids are available for what lengths of time.

Issue h Magmatic alteration of waste. Magma temperatures are expected to be of the order of 1000 °C. This high temperature, the presence of exsolving volatiles, and the many phases in the melt raise the possibility of chemical interaction, transformation, or dissolution of the waste. This is expected for glassified waste with a melt temperature below 1000 °C. While spent fuel on the other hand is refractory at these temperatures, we know nothing about its behavior in the melt.

Issue i Fracture development in dikes. Surface exposures of dikes display various degrees of fracturing. In consideration of the alteration of subsurface flow, the issue is whether the dike is a barrier to flow or, as a well-fractured, well-connected unit, is a conduit for flow. We presume it possible for a given dike to be both at different times and locations. What we need to know is what the controls are on the permeability of a dike.

Issue j Fracture development in sills. Like dikes, sills could also be barriers to flow, as suggested in several cartoons. One expects cooling fractures to form even in thick sills. How well-connected these fractures are would determine whether perched water might actually form on sills, whether sills are conduits, or whether sills are simply irrelevant for flow.

The issues summarized here are by no means an exhaustive set. They simply represent a few key concerns whose resolution allows modeling of the scenarios involved or pruning of the scenarios from the tree. Some of these issues are topics of Study Plan 8.3.1.8.1.2 (DOE, to be published)

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OCRWM
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Yucca Mountain Site
Characterization Project Office
US Department of Energy
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Las Vegas, NV 89193-8608

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Office of External Affairs
DOE Nevada Field Office
US Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

12 Technical Information Officer
DOE Nevada Field Office
US Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

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Office of Assistant Manager for
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Health
DOE Nevada Field Office
US Department of Energy
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Las Vegas, NV 89193-8518

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Environmental Protection and Division
DOE Nevada Field Office
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Las Vegas, NV 89193-8518

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Washington, DC 20555

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Mountain
Repository Project Branch
Division of Waste Management
US NRC
Washington, DC 20555

1 NRC Document Control Desk
Division of Waste Management
US NRC
Washington, DC 20555

1 Philip S. Justus
NRC Site Representive
301 E Stewart Avenue, Room 203
Las Vegas, NV 89101

1 E. P. Binnall
Field Systems Group Leader
Building 50B/4235
Lawrence Berkeley Laboratory
Berkeley, CA 94720

1 Center for Nuclear Waste
Regulatory Analyses
6220 Culebra Road
Drawer 28510
San Antonio, TX 78284

3 W. L. Clarke
Technical Project Officer - YMP
Attn: YMP/LRC
Lawrence Livermore National
Laboratory
P.O. Box 5514
Livermore, CA 94551

1 J. A. Blink
Deputy Project Leader
Lawrence Livermore National
Laboratory
101 Convention Center Drive
Suite 820, MS 527
Las Vegas, NV 89109

4 J. A. Canepa
Technical Project Officer - YMP
N-5, Mail Stop J521
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

1 H. N. Kalia
Exploratory Shaft Test Manager
Los Alamos National Laboratory
Mail Stop 527
101 Convention Center Dr., #820
Las Vegas, NV 89101

1 N. Z. Elkins
Deputy Technical Project Officer
Los Alamos National Laboratory
Mail Stop 527
101 Convention Center Dr., #820
Las Vegas, NV 89101

5 L. E. Shephard
Technical Project Officer - YMP
Sandia National Laboratories
Organization 6302
P.O. Box 5800
Albuquerque, NM 87185

1 J. F. Devine
Asst Director of Engineering Geology
US Geological Survey
106 National Center
12201 Sunrise Valley Drive
Reston, VA 22092

1 L. R. Hayes
Technical Project Officer
Yucca Mountain Project Branch
MS 425
US Geological Survey
P.O. Box 25046
Denver, CO 80225

1 V. R. Schneider
Asst. Chief Hydrologist--MS 414
Office of Program Coordination
and Technical Support
US Geological Survey
12201 Sunrise Valley Drive
Reston, VA 22092

1 J. S. Stuckless
Geologic Division Coordinator
MS 913
Yucca Mountain Project
US Geological Survey
P.O. Box 25046
Denver, CO 80225

1 D. H. Appel, Chief
Hydrologic Investigations Program
MS 421
US Geological Survey
P.O. Box 25046
Denver, CO 80225

1 E. J. Helley
Branch of Western Regional Geology
MS 427
US Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

1 R. W. Craig, Chief
Nevada Operations Office
US Geological Survey
101 Convention Center Drive
Suite 860, MS 509
Las Vegas, NV 89109

1 D. Zesiger
US Geological Survey
101 Conventional Center Drive
Suite 860, MS 509
Las Vegas, NV 89109

1 G. L. Ducret, Associate Chief
Yucca Mountain Project Division
US Geological Survey
P.O. Box 25046
421 Federal Center
Denver, CO 80225

1 A. L. Flint
US Geological Survey
MS 721
P.O. Box 327
Mercury, NV 89023

1 D. A. Beck
Water Resources Division, USGS
6770 S Paradise Road
Las Vegas, NV 89119

1 P. A. Glancy
US Geological Survey
Federal Building, Room 224
Carson City, NV 89701

1 Sherman S.C. Wu
Branch of Astrogeology
US Geological Survey
2255 N Gemini Drive
Flagstaff, AZ 86001

1 J. H. Sass - USGS
Branch of Tectonophysics
2255 N Gemini Drive
Flagstaff, AZ 86001

1 DeWayne Campbell
Technical Project Officer - YMP
US Bureau of Reclamation
Code D-3790
P.O. Box 25007
Denver, CO 80225

1 J. M. LaMonaca
Records Specialist
US Geological Survey
421 Federal Center
P.O. Box 25046
Denver, CO 80225

1 W. R. Keefer - USGS
913 Federal Center
P.O. Box 25046
Denver, CO 80225

1 M. D. Voegele
Technical Project Officer - YMP
SAIC
101 Convention Center Drive
Suite 407
Las Vegas, NV 89109

2 L. D. Foust
Nevada Site Manager
TRW Environmental Safety
Systems
101 Convention Center Drive
Suite 540, MS 423
Las Vegas, NV 89109

1 C. E. Ezra
YMP Support Office Manager
EG&G Energy Measurements Inc
MS V-02
P.O. Box 1912
Las Vegas, NV 89125

1 E. L. Snow, Program Manager
Roy F. Weston Inc
955 L'Enfant Plaza SW
Washington, DC 20024

1 Technical Information Center
Roy F. Weston Inc
955 L'Enfant Plaza SW
Washington, DC 20024

1 D. Hedges, Vice President, QA
Roy F. Weston Inc
4425 Spring Mountain Road
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Las Vegas, NV 89102

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1 Carlos G. Bell Jr
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Civil and Mechanical Engineering Dept.
University of Nevada, Las Vegas
4505 S Maryland Parkway
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3 R. R. Loux
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Evergreen Center, Suite 252
1802 N. Carson Street
Carson City, NV 89710

1 C. H. Johnson
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Agency for Nuclear Projects
State of Nevada
Evergreen Center, Suite 252
1802 N. Carson Street
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Desert Research Institute
P.O. Box 60220
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1 Dennis Bechtel, Coordinator
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Clark County Department of
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1 Yucca Mountain Information
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1 Planning Department
Nye County
P.O. Box 153
Tonopah, NV 89049

1 Florindo Mariani
White Pine County Nuclear
Waste Project Office
457 Fifth Street
Ely, NV 89301

5 Judy Foremaster
City of Caliente Nuclear Waste
Project Office
P.O. Box 158
Caliente, NV 89008

1 Jason Pitts
Lincoln County Nuclear Waste
Project Office
Lincoln County Courthouse
Pioche, NV 89043

1 Economic Development Dept.
City of Las Vegas
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Las Vegas, NV 89101

1 Commmunity Planning and
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1 Steve Bradhurst
P.O. Box 1510
Reno, NV 89505

1 Michael L. Baughman
35 Clark Road
Fiskdale, MA 01518

1 Glenn Van Roekel
Director of Community
Development
City of Caliente
P.O. Box 158
Caliente, NV 89008

1 Ray Williams, Jr
P.O. Box 10
Austin, NV 89310

1 R. F. Pritchett
Technical Project Officer - YMP
Reynolds Electrical &
Engineering Co Inc
MS 408
P.O. Box 98521
Las Vegas, NV 89193-8521

1 Charles Thistlethwaite, AICP
Associate Planner
Inyo County Planning Department
Drawer L
Independence, CA 93526

1 Les Bradshaw
Nye County District Attorney
P.O. Box 593
Tonopah, NV 89049

1 Dr. Moses Karakouzian
1751 E Reno #125
Las Vegas, NV 89119

1 J. Wang
Lawrence Berkeley Laboratory
Earth Sciences Division
1 Cyclotron Road
Berkeley, CA 94720

1 D. Hoxie
US Geological Survey
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Austin, TX 78731

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Livermore, CA 94550

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Lawrence Livermore National
Laboratory
P.O. Box 808
MS L206
Livermore, CA 94550

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Suite 820
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1 M.D. Carr
US Geological Survey
MS 975
345 Middlefield Road
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US Geological Survey
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Lawrence Livermore National Laboratory
MS L-206
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1 William Dudley, Jr.
US Geological Survey
MS 425
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Denver, CO 80225

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SAIC
101 Convention Center Drive
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1 Leon Reiter
Nuclear Waste Technical Review Board
1100 Wilson Blvd
Suite 910
Arlington, VA 22209-2297

1 Robert Luce
Nuclear Waste Technical Review Board
1100 Wilson Blvd
Suite 910
Arlington, VA 22209-2297

1 Claudia Newbury
Yucca Mountain Project Office
US Department of Energy
P.O. Box 98608
MS 523
Las Vegas, NV 89193-8518

1 J.M. Boak
Yucca Mountain Project Office
US Department of Energy
P.O. Box 98608
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Yucca Mountain Project Office
US Department of Energy
P.O. Box 98608
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MS 523
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1 Chris Fridrich
Yucca Mountain Project
US Geological Survey
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Lawrence Livermore National Laboratory
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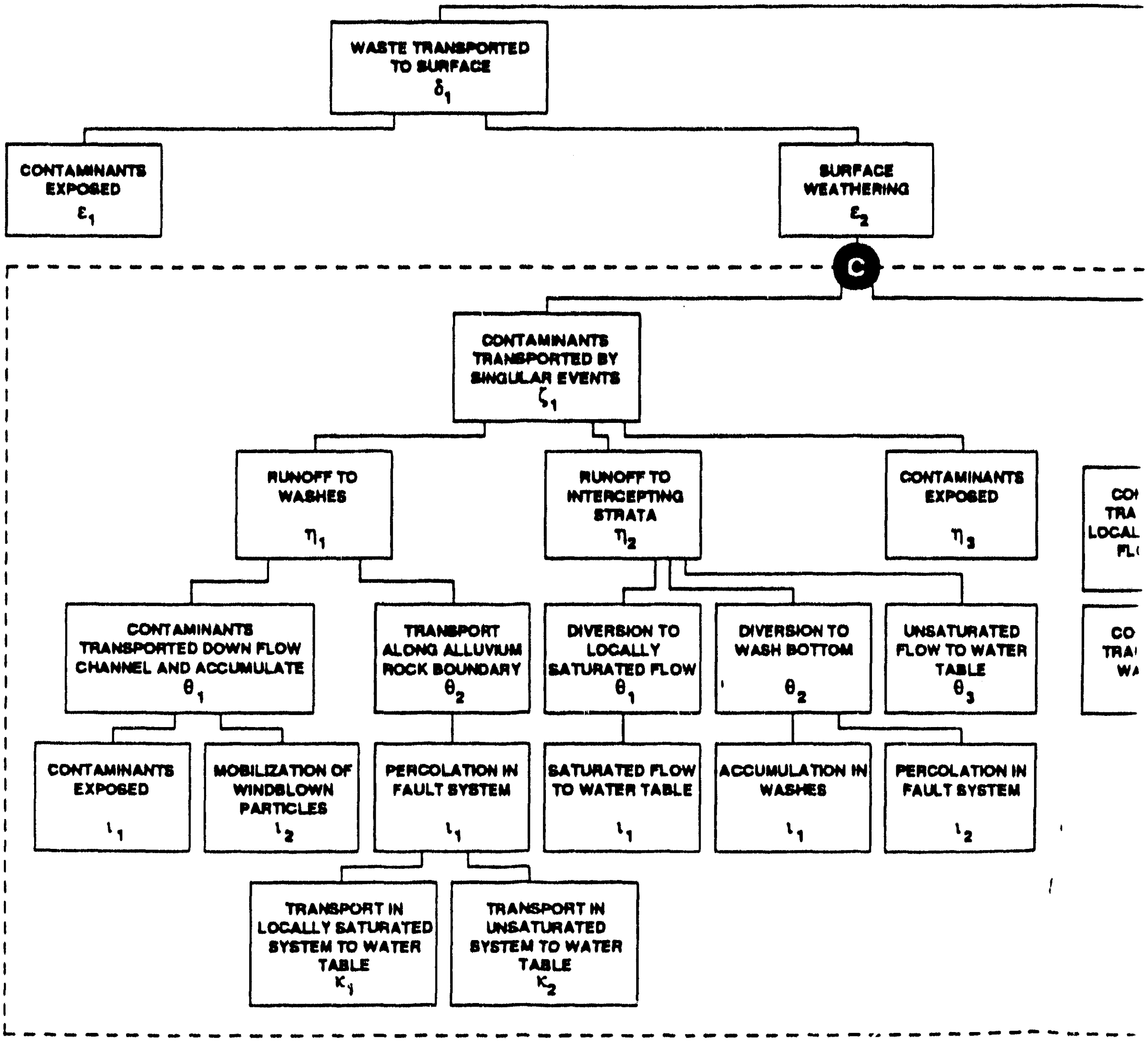
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RUNOFF TO INTERCEPTING STRATA η_2
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DIVERSION TO WASH BOTTOM θ_2
UNSATURATED FLOW TO WATER TABLE θ_3
CO TRA WA
CONTAMINANTS EXPOSED ι_1
MOBILIZATION OF WINDBLOWN PARTICLES ι_2
PERCOLATION IN FAULT SYSTEM ι_1
SATURATED FLOW TO WATER TABLE ι_1
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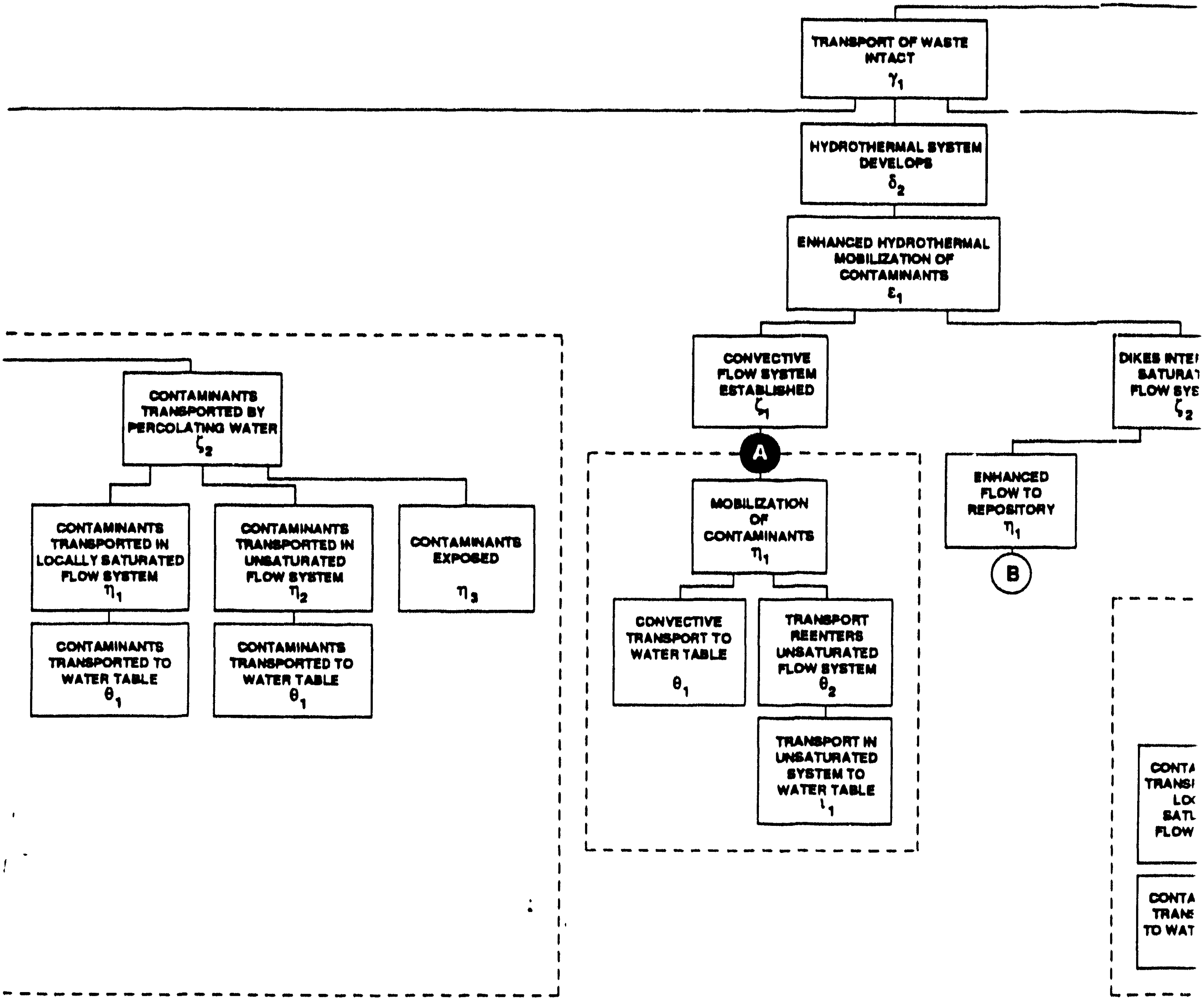
PERCOLATION IN FAULT SYSTEM ι_2
TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE κ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE κ_2


TRANSPORT OF WASTE INTACT γ_1
HYDROTHERMAL SYSTEM DEVELOPS δ_2
ENHANCED HYDROTHERMAL MOBILIZATION OF CONTAMINANTS ε_1
CONVECTIVE FLOW SYSTEM ESTABLISHED ζ_1
DIKES INTE SATURA FLOW SYS ζ_2
A
MOBILIZATION OF CONTAMINANTS η_1
CONVECTIVE TRANSPORT TO WATER TABLE θ_1
TRANSPORT REENTERS UNSATURATED FLOW SYSTEM θ_2
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE ι_1
ENHANCED FLOW TO REPOSITORY η_1
B
CONTAMINANTS TRANSPORTED BY PERCOLATING WATER ζ_2
CONTAMINANTS TRANSPORTED IN LOCALLY SATURATED FLOW SYSTEM η_1
CONTAMINANTS TRANSPORTED IN UNSATURATED FLOW SYSTEM η_2
CONTAMINANTS EXPOSED η_3
CONTAMINANTS TRANSPORTED TO WATER TABLE θ_1
CONTAMINANTS TRANSPORTED TO WATER TABLE θ_1
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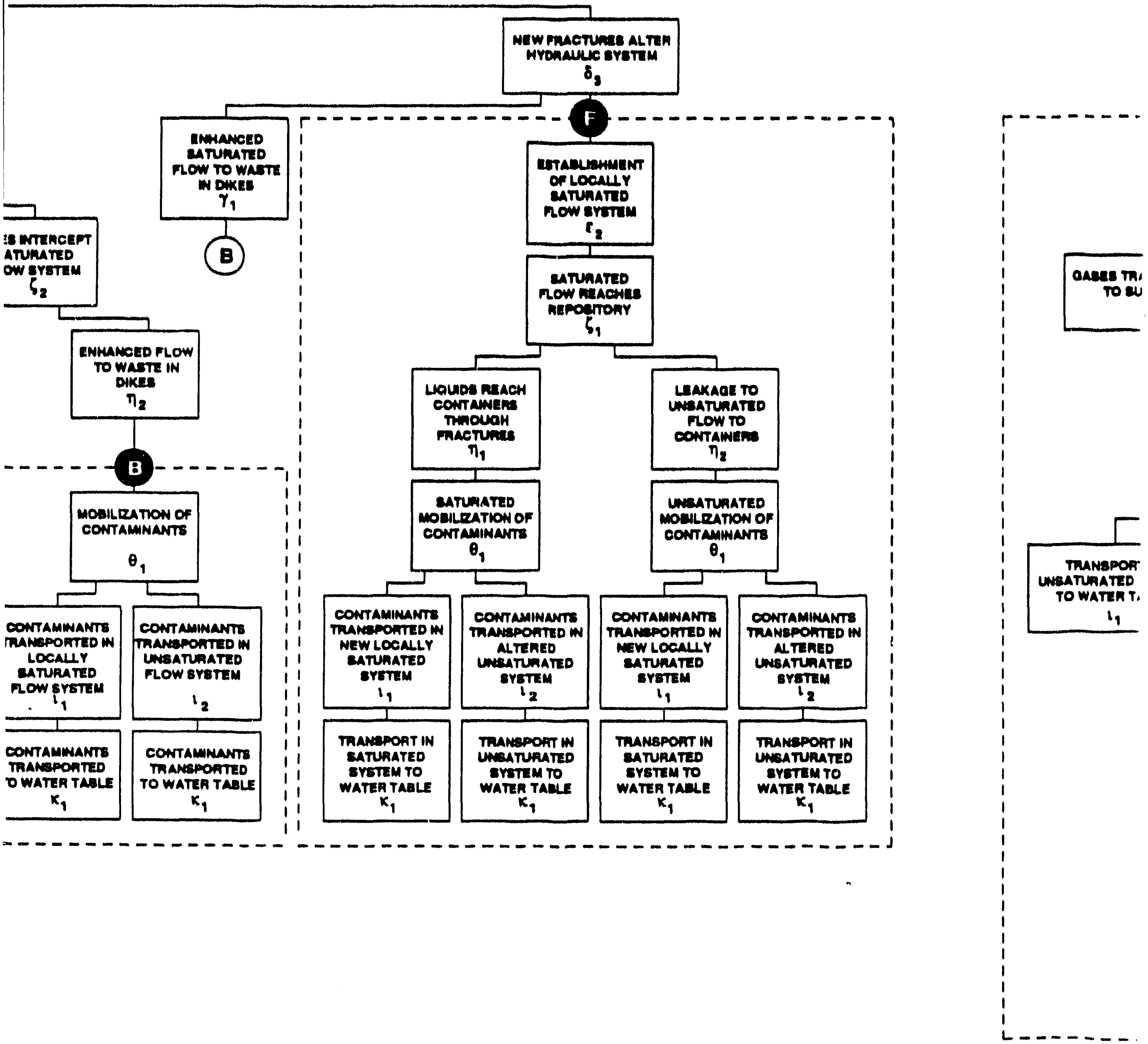
NEW FRACTURES ALTER HYDRAULIC SYSTEM δ_3
F
ENHANCED SATURATED FLOW TO WASTE IN DIKES γ_1
B
ES INTERCEPT ATURATED OW SYSTEM ζ_2
ENHANCED FLOW TO WASTE IN DIKES η_2
B
MOBILIZATION OF CONTAMINANTS θ_1
CONTAMINANTS TRANSPORTED IN LOCALLY SATURATED FLOW SYSTEM ι_1
CONTAMINANTS TRANSPORTED IN UNSATURATED FLOW SYSTEM ι_2
CONTAMINANTS TRANSPORTED O WATER TABLE κ_1
CONTAMINANTS TRANSPORTED TO WATER TABLE κ_1
ESTABLISHMENT OF LOCALLY SATURATED FLOW SYSTEM ε_2
SATURATED FLOW REACHES REPOSITORY ζ_1
LIQUIDS REACH CONTAINERS THROUGH FRACTURES η_1
LEAKAGE TO UNSATURATED FLOW TO CONTAINERS η_2
SATURATED MOBILIZATION OF CONTAMINANTS θ_1
UNSATURATED MOBILIZATION OF CONTAMINANTS θ_1
CONTAMINANTS TRANSPORTED IN NEW LOCALLY SATURATED SYSTEM ι_1
CONTAMINANTS TRANSPORTED IN ALTERED UNSATURATED SYSTEM ι_2
CONTAMINANTS TRANSPORTED IN NEW LOCALLY SATURATED SYSTEM ι_1
CONTAMINANTS TRANSPORTED IN ALTERED UNSATURATED SYSTEM ι_2
TRANSPORT IN SATURATED SYSTEM TO WATER TABLE κ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE κ_1
TRANSPORT IN SATURATED SYSTEM TO WATER TABLE κ_1
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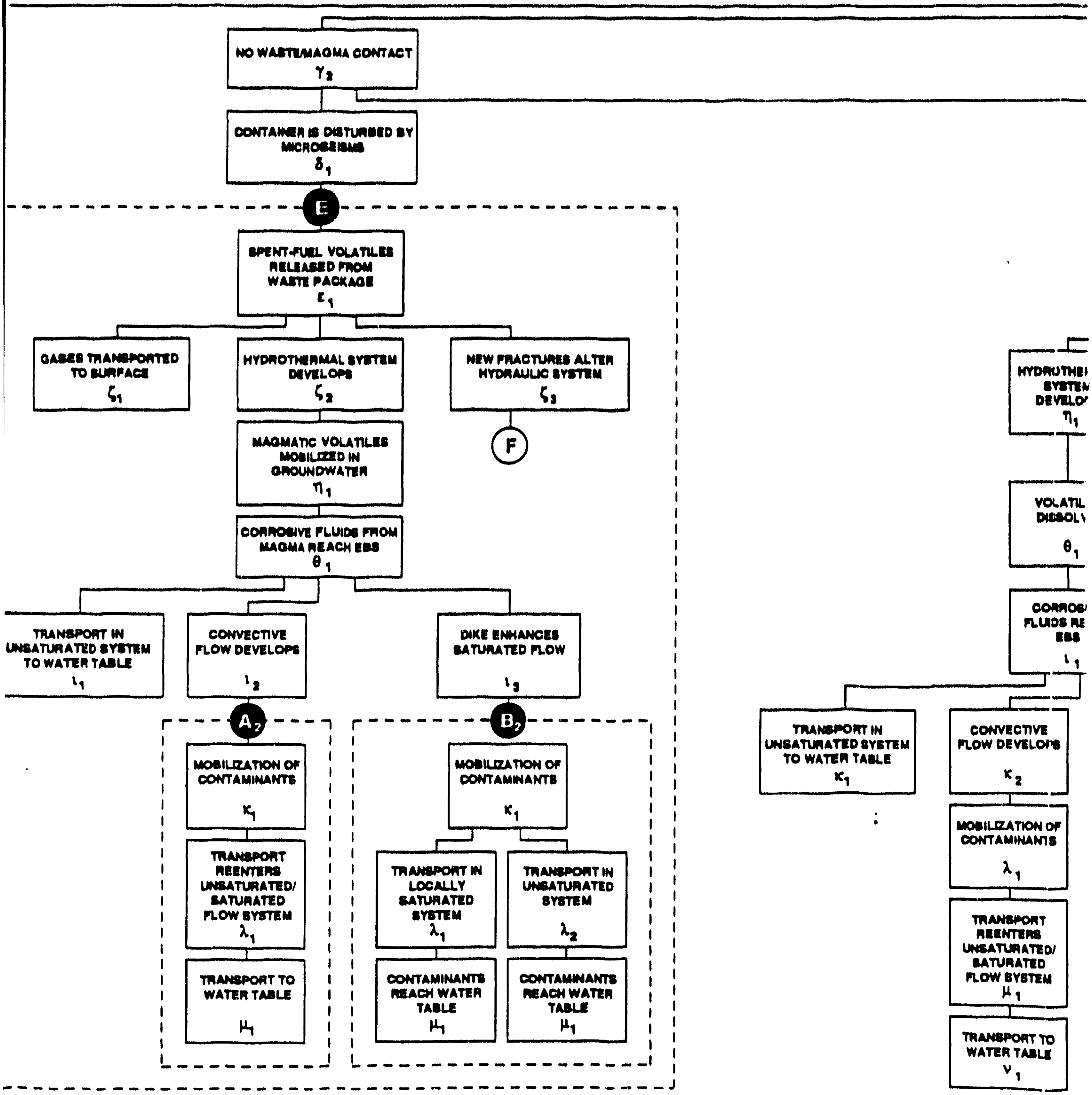
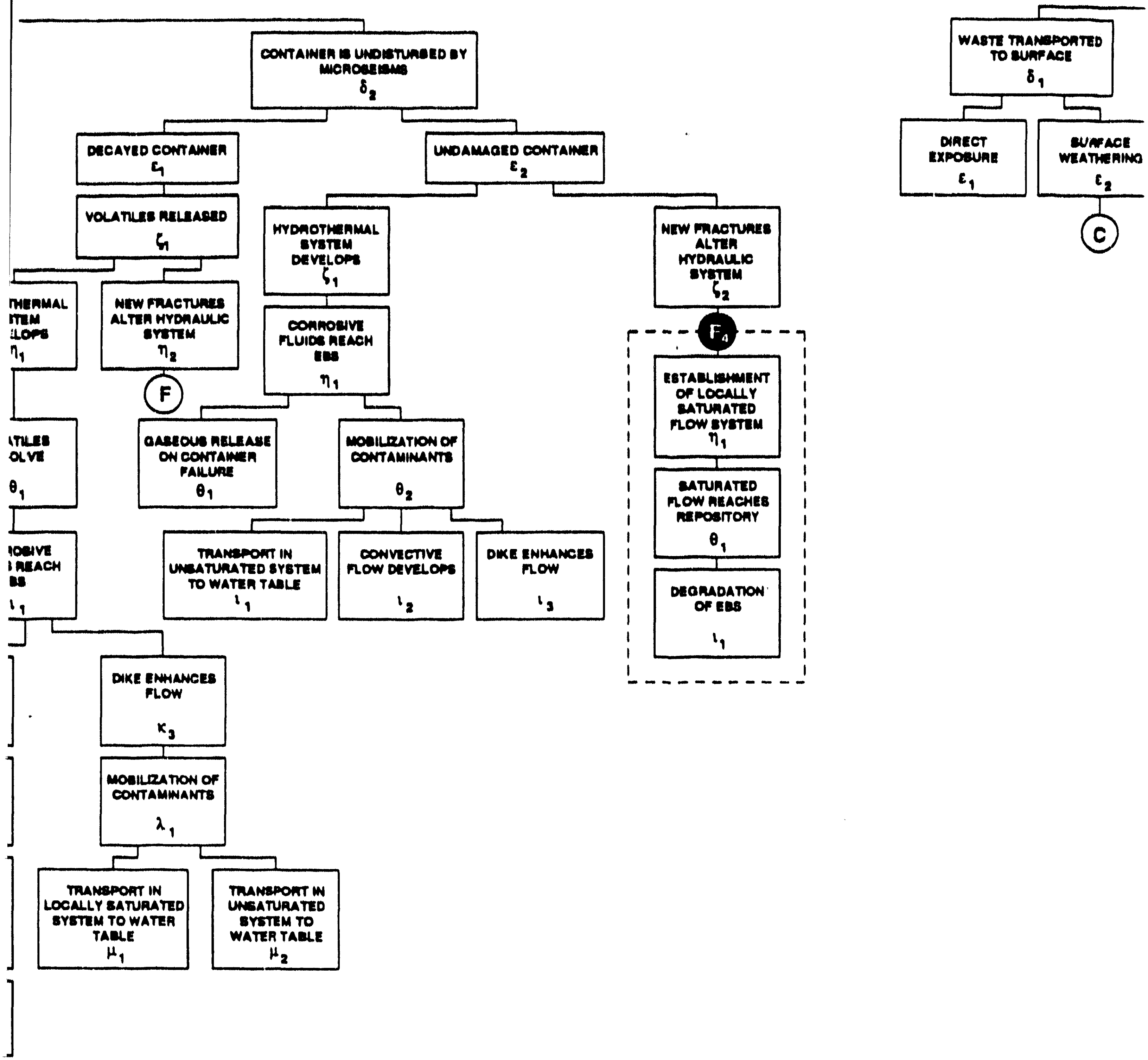
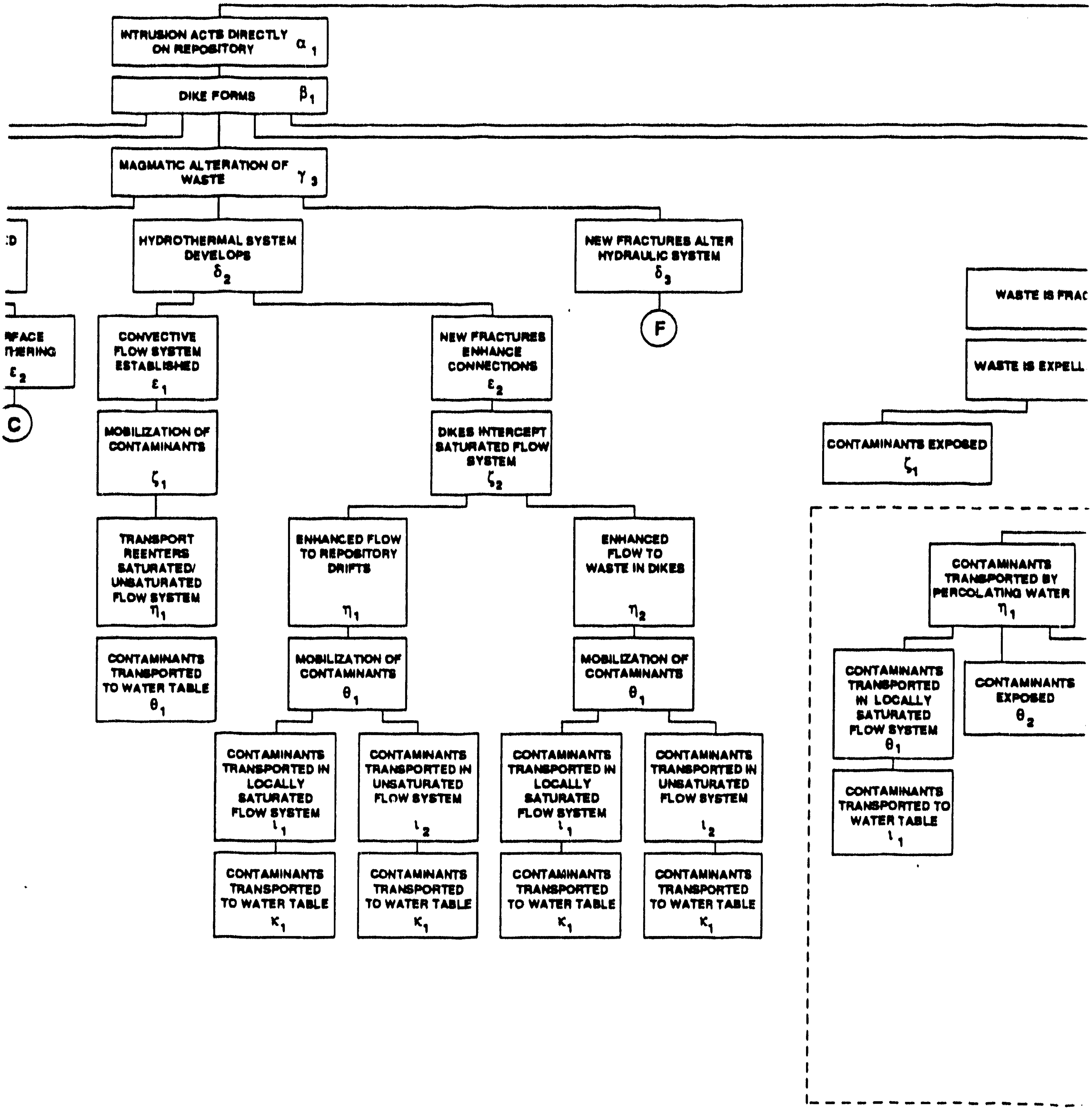

NO WASTE/MAGMA CONTACT γ_2
CONTAINER IS DISTURBED BY MICROSEISMS δ_1
E
SPENT-FUEL VOLATILES RELEASED FROM WASTE PACKAGE ε_1
GASES TRANSPORTED TO SURFACE ζ_1
HYDROTHERMAL SYSTEM DEVELOPS ζ_2
NEW FRACTURES ALTER HYDRAULIC SYSTEM ζ_3
F
MAGMATIC VOLATILES MOBILIZED IN GROUNDWATER η_1
CORROSIVE FLUIDS FROM MAGMA REACH EBS θ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE ι_1
CONVECTIVE FLOW DEVELOPS ι_2
DIKE ENHANCES SATURATED FLOW ι_3
A_2
MOBILIZATION OF CONTAMINANTS κ_1
TRANSPORT REENTERS UNSATURATED/ SATURATED FLOW SYSTEM λ_1
TRANSPORT TO WATER TABLE μ_1
B_2
MOBILIZATION OF CONTAMINANTS κ_1
TRANSPORT IN LOCALLY SATURATED SYSTEM λ_1
TRANSPORT IN UNSATURATED SYSTEM λ_2
CONTAMINANTS REACH WATER TABLE μ_1
CONTAMINANTS REACH WATER TABLE μ_1
HYDROTHEI SYSTEM DEVELO η_1
VOLATIL DISSOL θ_1
CORROS FLUIDS RE EBS ι_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE κ_1
CONVECTIVE FLOW DEVELOPS κ_2
MOBILIZATION OF CONTAMINANTS λ_1
TRANSPORT REENTERS UNSATURATED/ SATURATED FLOW SYSTEM μ_1
TRANSPORT TO WATER TABLE ν_1


CONTAINER IS UNDISTURBED BY MICROSEISMS δ_2
DECAYED CONTAINER ε_1
UNDAMAGED CONTAINER ε_2
VOLATILES RELEASED ζ_1
HYDROTHERMAL SYSTEM DEVELOPS ζ_1
NEW FRACTURES ALTER HYDRAULIC SYSTEM ζ_2
THERMAL
STEM
ELOPS η_1
NEW FRACTURES ALTER HYDRAULIC SYSTEM η_2
F
CORROSIVE FLUIDS REACH EBS η_1
F4
ESTABLISHMENT OF LOCALLY SATURATED FLOW SYSTEM η_1
ATILES
OLVE θ_1
GASEOUS RELEASE ON CONTAINER FAILURE θ_1
MOBILIZATION OF CONTAMINANTS θ_2
SATURATED FLOW REACHES REPOSITORY θ_1
ROSIVE
REACH
BS ι_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE ι_1
CONVECTIVE FLOW DEVELOPS ι_2
DIKE ENHANCES FLOW ι_3
DEGRADATION OF EBS ι_1
DIKE ENHANCES FLOW κ_3
MOBILIZATION OF CONTAMINANTS λ_1
TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE μ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE μ_2
WASTE TRANSPORTED TO SURFACE δ_1
DIRECT EXPOSURE ε_1
SURFACE WEATHERING ε_2
C


INTRUSION ACTS DIRECTLY ON REPOSITORY α_1
DIKE FORMS β_1
MAGMATIC ALTERATION OF WASTE γ_3
:D
HYDROTHERMAL SYSTEM DEVELOPS δ_2
NEW FRACTURES ALTER HYDRAULIC SYSTEM δ_3
F
RFACE THERING ε_2
C
CONVECTIVE FLOW SYSTEM ESTABLISHED ε_1
NEW FRACTURES ENHANCE CONNECTIONS ε_2
WASTE IS FRAC
WASTE IS EXPELL
MOBILIZATION OF CONTAMINANTS ζ_1
DIKES INTERCEPT SATURATED FLOW SYSTEM ζ_2
CONTAMINANTS EXPOSED ζ_1
TRANSPORT REENTERS SATURATED/ UNSATURATED FLOW SYSTEM η_1
ENHANCED FLOW TO REPOSITORY DRIFTS η_1
ENHANCED FLOW TO WASTE IN DIKES η_2
CONTAMINANTS TRANSPORTED BY PERCOLATING WATER η_1
CONTAMINANTS TRANSPORTED TO WATER TABLE θ_1
MOBILIZATION OF CONTAMINANTS θ_1
MOBILIZATION OF CONTAMINANTS θ_1
CONTAMINANTS TRANSPORTED IN LOCALLY SATURATED FLOW SYSTEM θ_1
CONTAMINANTS EXPOSED θ_2
CONTAMINANTS TRANSPORTED IN LOCALLY SATURATED FLOW SYSTEM ι_1
CONTAMINANTS TRANSPORTED IN UNSATURATED FLOW SYSTEM ι_2
CONTAMINANTS TRANSPORTED IN LOCALLY SATURATED FLOW SYSTEM ι_1
CONTAMINANTS TRANSPORTED IN UNSATURATED FLOW SYSTEM ι_2
CONTAMINANTS TRANSPORTED TO WATER TABLE ι_1
CONTAMINANTS TRANSPORTED TO WATER TABLE κ_1
CONTAMINANTS TRANSPORTED TO WATER TABLE κ_1
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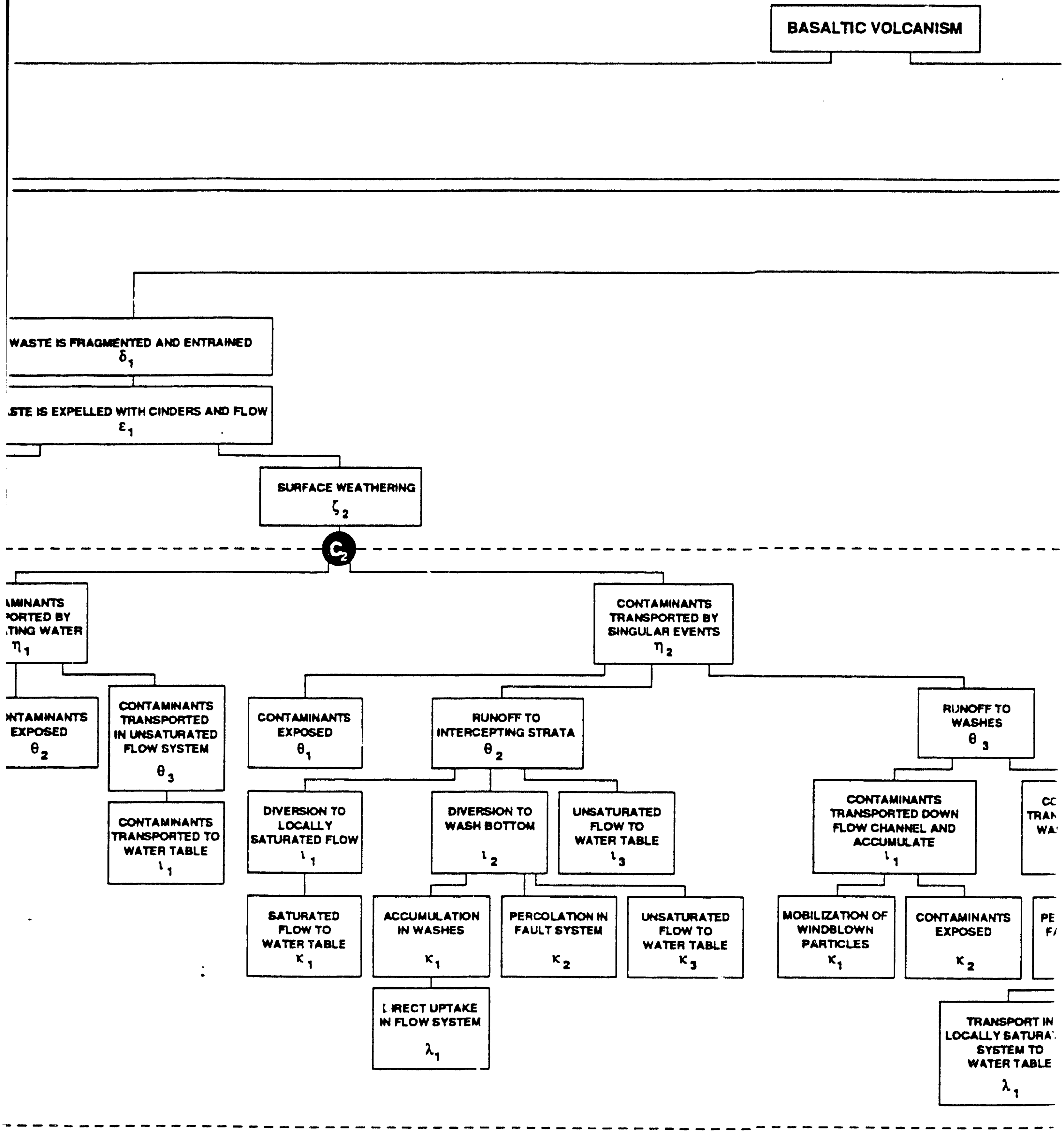
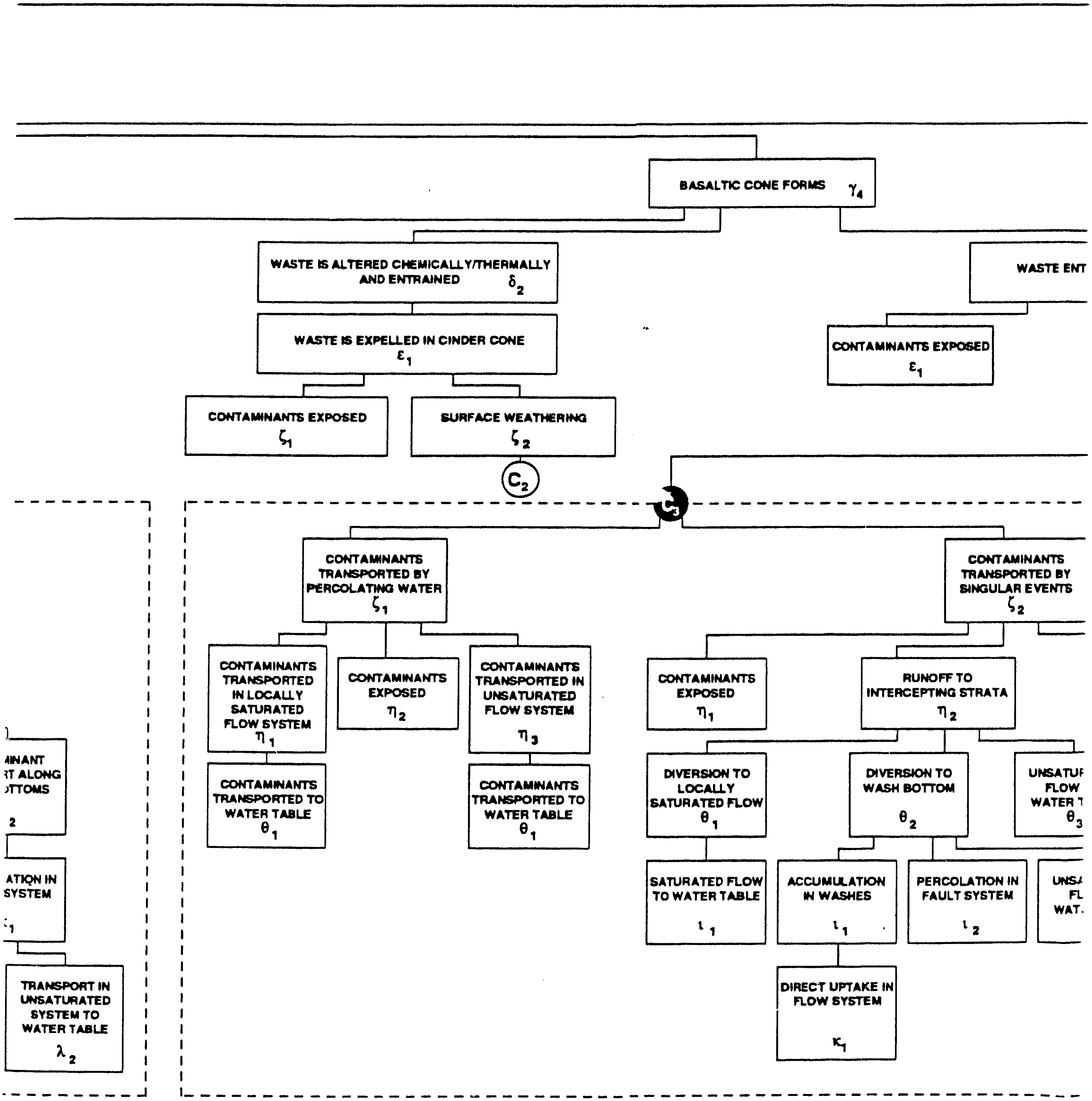

BASALTIC VOLCANISM
WASTE IS FRAGMENTED AND ENTRAINED δ_1
STE IS EXPELLED WITH CINDERS AND FLOW ε_1
SURFACE WEATHERING ζ_2
C_2
MINANTS PORTED BY TING WATER η_1
CONTAMINANTS TRANSPORTED BY SINGULAR EVENTS η_2
NTAMINANTS EXPOSED θ_2
CONTAMINANTS TRANSPORTED IN UNSATURATED FLOW SYSTEM θ_3
CONTAMINANTS TRANSPORTED TO WATER TABLE ι_1
CONTAMINANTS EXPOSED θ_1
RUNOFF TO INTERCEPTING STRATA θ_2
RUNOFF TO WASHES θ_3
DIVERSION TO LOCALLY SATURATED FLOW ι_1
DIVERSION TO WASH BOTTOM ι_2
UNSATURATED FLOW TO WATER TABLE ι_3
CONTAMINANTS TRANSPORTED DOWN FLOW CHANNEL AND ACCUMULATE ι_1
CC TRAN WA
SATURATED FLOW TO WATER TABLE κ_1
ACCUMULATION IN WASHES κ_1
PERCOLATION IN FAULT SYSTEM κ_2
UNSATURATED FLOW TO WATER TABLE κ_3
MOBILIZATION OF WINDBLOWN PARTICLES κ_1
CONTAMINANTS EXPOSED κ_2
PE F
DIRECT UPTAKE IN FLOW SYSTEM λ_1
TRANSPORT IN LOCALLY SATURA SYSTEM TO WATER TABLE λ_1


BASALTIC CONE FORMS γ_4
WASTE IS ALTERED CHEMICALLY/THERMALLY AND ENTRAINED δ_2
WASTE ENT
WASTE IS EXPELLED IN CINDER CONE ε_1
CONTAMINANTS EXPOSED ε_1
CONTAMINANTS EXPOSED ζ_1
SURFACE WEATHERING ζ_2
C_2
C_3
CONTAMINANTS TRANSPORTED BY PERCOLATING WATER ζ_1
CONTAMINANTS TRANSPORTED BY SINGULAR EVENTS ζ_2
CONTAMINANTS TRANSPORTED IN LOCALLY SATURATED FLOW SYSTEM η_1
CONTAMINANTS EXPOSED η_2
CONTAMINANTS TRANSPORTED IN UNSATURATED FLOW SYSTEM η_3
CONTAMINANTS EXPOSED η_1
RUNOFF TO INTERCEPTING STRATA η_2
CONTAMINANTS TRANSPORTED TO WATER TABLE θ_1
CONTAMINANTS TRANSPORTED TO WATER TABLE θ_1
DIVERSION TO LOCALLY SATURATED FLOW θ_1
DIVERSION TO WASH BOTTOM θ_2
UNSATUR FLOW WATER T θ_3
SATURATED FLOW TO WATER TABLE ι_1
ACCUMULATION IN WASHES ι_1
PERCOLATION IN FAULT SYSTEM ι_2
UNSA FL WAT.
DIRECT UPTAKE IN FLOW SYSTEM κ_1
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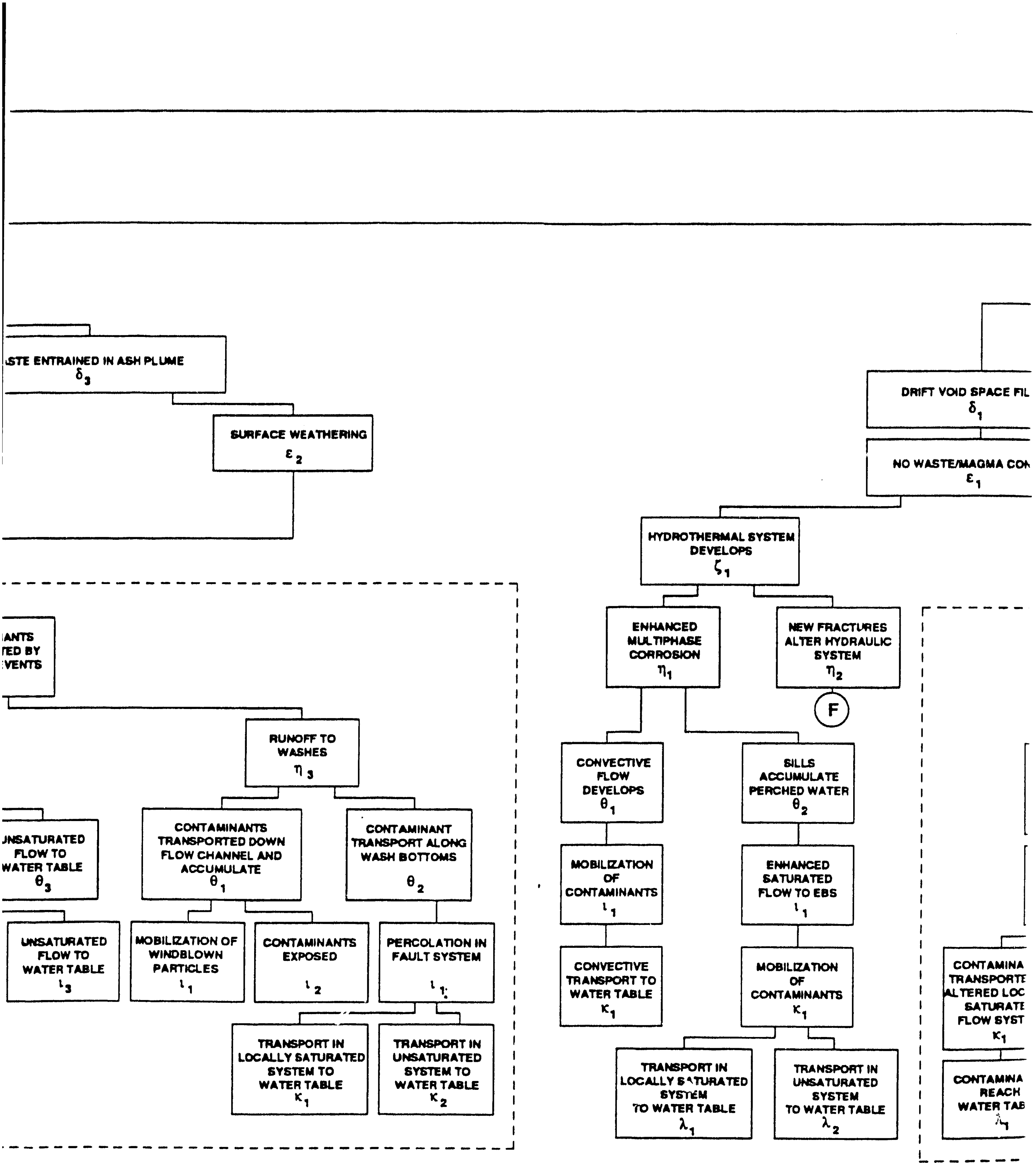
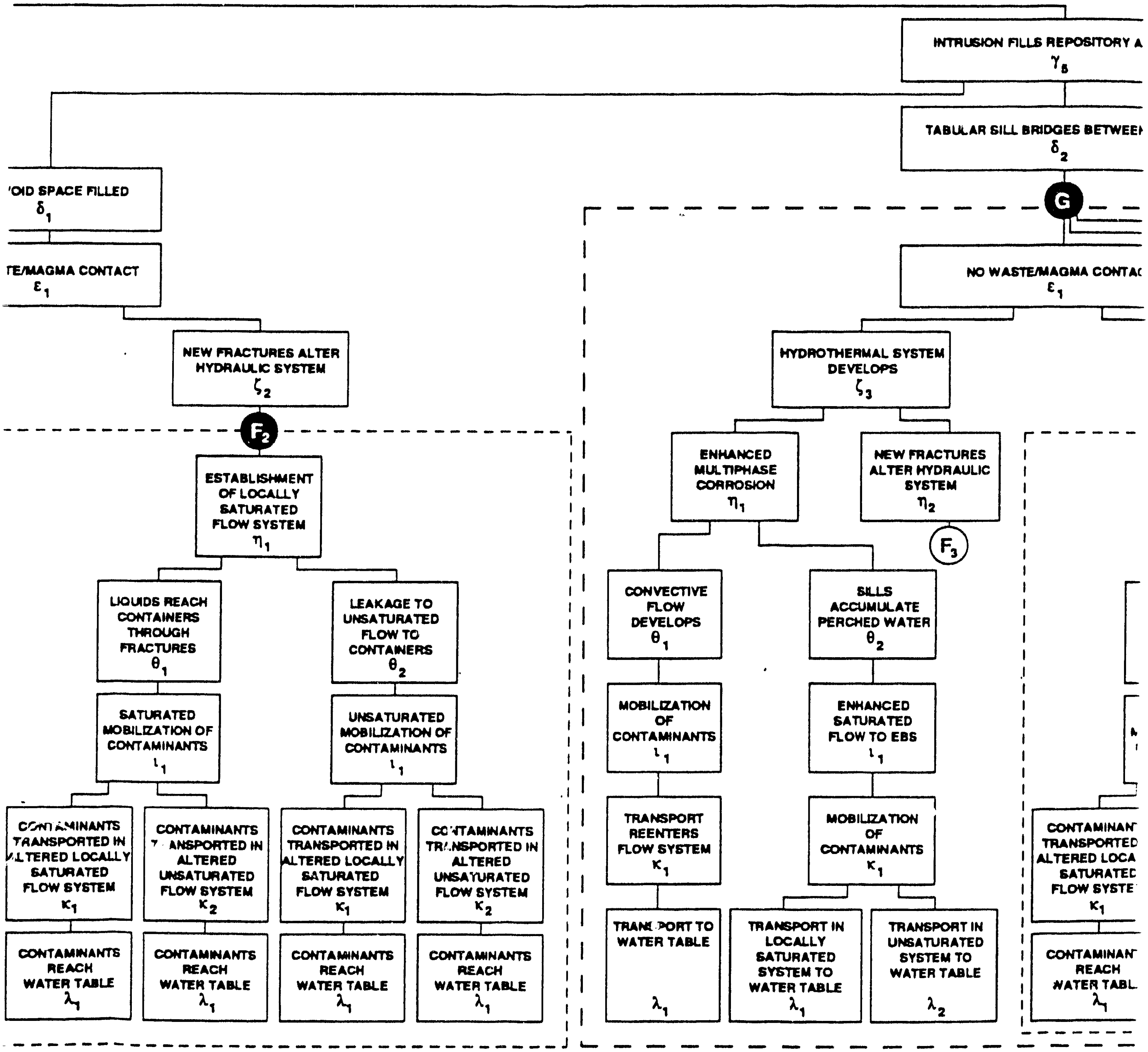
ATION IN SYSTEM 1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE λ_2



STE ENTRAINED IN ASH PLUME δ_3
SURFACE WEATHERING ε_2
DRIFT VOID SPACE FIL δ_1
NO WASTE/MAGMA CON ε_1
HYDROTHERMAL SYSTEM DEVELOPS ζ_1
ANTS TED BY VENTS
ENHANCED MULTIPHASE CORROSION η_1
NEW FRACTURES ALTER HYDRAULIC SYSTEM η_2
F
RUNOFF TO WASHES η_3
CONVECTIVE FLOW DEVELOPS θ_1
SILLS ACCUMULATE PERCHED WATER θ_2
UNSATURATED FLOW TO WATER TABLE θ_3
CONTAMINANTS TRANSPORTED DOWN FLOW CHANNEL AND ACCUMULATE θ_1
CONTAMINANT TRANSPORT ALONG WASH BOTTOMS θ_2
MOBILIZATION OF CONTAMINANTS ι_1
ENHANCED SATURATED FLOW TO EBS ι_1
UNSATURATED FLOW TO WATER TABLE ι_3
MOBILIZATION OF WINDBLOWN PARTICLES ι_1
CONTAMINANTS EXPOSED ι_2
PERCOLATION IN FAULT SYSTEM ι_1
CONVECTIVE TRANSPORT TO WATER TABLE κ_1
MOBILIZATION OF CONTAMINANTS κ_1
CONTAMINA TRANSPORTE ALTERED LOC SATURATE FLOW SYST κ_1
TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE κ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE κ_2
TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE λ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE λ_2
CONTAMINA REACH WATER TAB λ_1


INTRUSION FILLS REPOSITORY A
γ_5
TABULAR SILL BRIDGES BETWEEN
δ_2
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TE/MAGMA CONTACT
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NEW FRACTURES ALTER HYDRAULIC SYSTEM
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ESTABLISHMENT OF LOCALLY SATURATED FLOW SYSTEM
η_1
LIQUIDS REACH CONTAINERS THROUGH FRACTURES
θ_1
LEAKAGE TO UNSATURATED FLOW TO CONTAINERS
θ_2
SATURATED MOBILIZATION OF CONTAMINANTS
ι_1
UNSATURATED MOBILIZATION OF CONTAMINANTS
ι_1
CONTAMINANTS TRANSPORTED IN ALTERED LOCALLY SATURATED FLOW SYSTEM
κ_1
CONTAMINANTS TRANSPORTED IN ALTERED UNSATURATED FLOW SYSTEM
κ_2
CONTAMINANTS TRANSPORTED IN ALTERED LOCALLY SATURATED FLOW SYSTEM
κ_1
CONTAMINANTS TRANSPORTED IN ALTERED UNSATURATED FLOW SYSTEM
κ_2
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λ_1
CONTAMINANTS REACH WATER TABLE
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HYDROTHERMAL SYSTEM DEVELOPS
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ENHANCED MULTIPHASE CORROSION
η_1
NEW FRACTURES ALTER HYDRAULIC SYSTEM
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CONVECTIVE FLOW DEVELOPS
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SILLS ACCUMULATE PERCHED WATER
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MOBILIZATION OF CONTAMINANTS
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ENHANCED SATURATED FLOW TO EBS
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TRANSPORT REENTERS FLOW SYSTEM
κ_1
MOBILIZATION OF CONTAMINANTS
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TRANSPORT TO WATER TABLE
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TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE
λ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE
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CONTAMINAN' TRANSPORTED ALTERED LOCA SATURATED FLOW SYSTE
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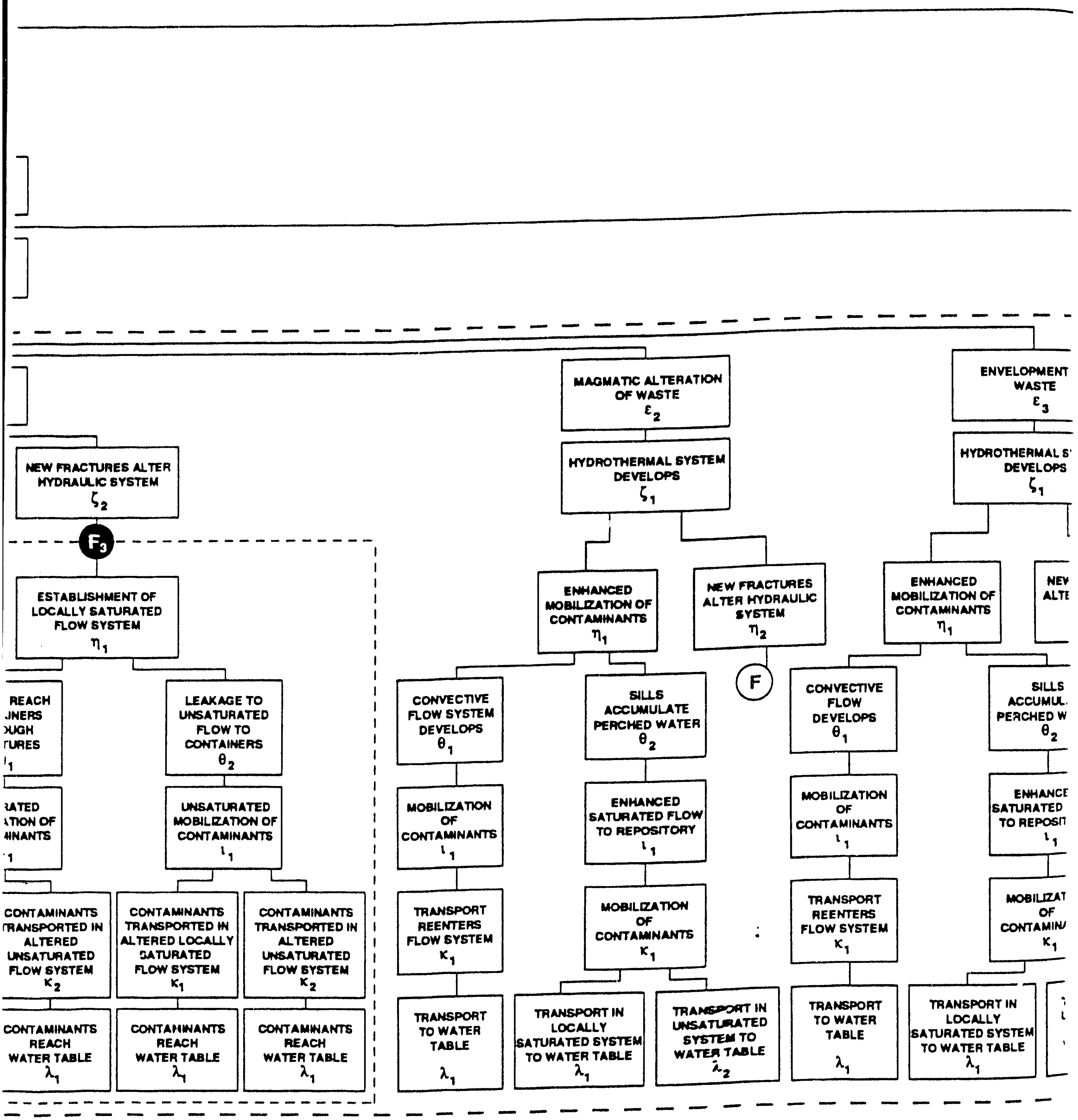

NEW FRACTURES ALTER HYDRAULIC SYSTEM ζ_2
F3
ESTABLISHMENT OF LOCALLY SATURATED FLOW SYSTEM η_1
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LEAKAGE TO UNSATURATED FLOW TO CONTAINERS θ_2
RATED
ATION OF
MINANTS
1
UNSATURATED MOBILIZATION OF CONTAMINANTS ι_1
CONTAMINANTS TRANSPORTED IN ALTERED UNSATURATED FLOW SYSTEM κ_2
CONTAMINANTS TRANSPORTED IN ALTERED LOCALLY SATURATED FLOW SYSTEM κ_1
CONTAMINANTS TRANSPORTED IN ALTERED UNSATURATED FLOW SYSTEM κ_2
CONTAMINANTS REACH WATER TABLE λ_1
CONTAMINANTS REACH WATER TABLE λ_1
CONTAMINANTS REACH WATER TABLE λ_1
MAGMATIC ALTERATION OF WASTE ε_2
HYDROTHERMAL SYSTEM DEVELOPS ζ_1
ENHANCED MOBILIZATION OF CONTAMINANTS η_1
NEW FRACTURES ALTER HYDRAULIC SYSTEM η_2
F
CONVECTIVE FLOW SYSTEM DEVELOPS θ_1
SILLS ACCUMULATE PERCHED WATER θ_2
MOBILIZATION OF CONTAMINANTS ι_1
ENHANCED SATURATED FLOW TO REPOSITORY ι_1
TRANSPORT REENTERS FLOW SYSTEM κ_1
MOBILIZATION OF CONTAMINANTS κ_1
TRANSPORT TO WATER TABLE λ_1
TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE λ_1
TRANSPORT IN UNSATURATED SYSTEM TO WATER TABLE λ_2
ENVELOPMENT WASTE ε_3
HYDROTHERMAL S DEVELOPS ζ_1
ENHANCED MOBILIZATION OF CONTAMINANTS η_1
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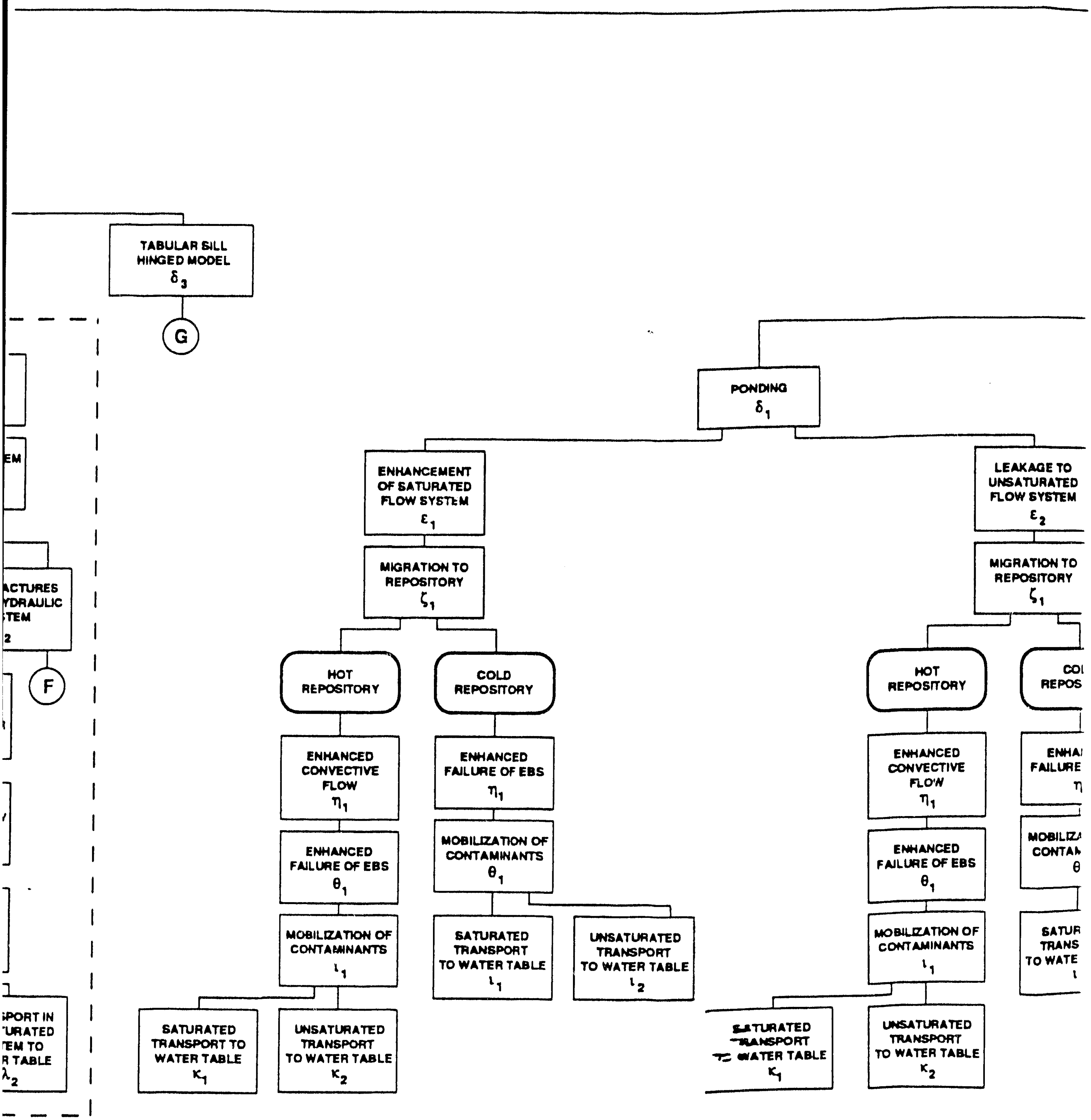
CONVECTIVE FLOW DEVELOPS θ_1
SILLS ACCUMUL PERCHED W θ_2
MOBILIZATION OF CONTAMINANTS ι_1
ENHANCE SATURATED TO REPOSI ι_1
TRANSPORT REENTERS FLOW SYSTEM κ_1
MOBILIZAT OF CONTAMIN κ_1
TRANSPORT TO WATER TABLE λ_1
TRANSPORT IN LOCALLY SATURATED SYSTEM TO WATER TABLE λ_1


TABULAR SILL HINGED MODEL δ_3
G
PONDING δ_1
ENHANCEMENT OF SATURATED FLOW SYSTEM ε_1
LEAKAGE TO UNSATURATED FLOW SYSTEM ε_2
MIGRATION TO REPOSITORY ζ_1
MIGRATION TO REPOSITORY ζ_1
HOT REPOSITORY
COLD REPOSITORY
HOT REPOSITORY
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ENHANCED CONVECTIVE FLOW η_1
ENHANCED FAILURE OF EBS η_1
ENHANCED CONVECTIVE FLOW η_1
ENHA FAILURE η
ENHANCED FAILURE OF EBS θ_1
MOBILIZATION OF CONTAMINANTS θ_1
ENHANCED FAILURE OF EBS θ_1
MOBILIZA CONTAM θ
MOBILIZATION OF CONTAMINANTS ι_1
SATURATED TRANSPORT TO WATER TABLE ι_1
UNSATURATED TRANSPORT TO WATER TABLE ι_2
MOBILIZATION OF CONTAMINANTS ι_1
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SATURATED TRANSPORT TO WATER TABLE κ_1
UNSATURATED TRANSPORT TO WATER TABLE κ_2
SATURATED TRANSPORT WATER TABLE κ_1
UNSATURATED TRANSPORT TO WATER TABLE κ_2
EM
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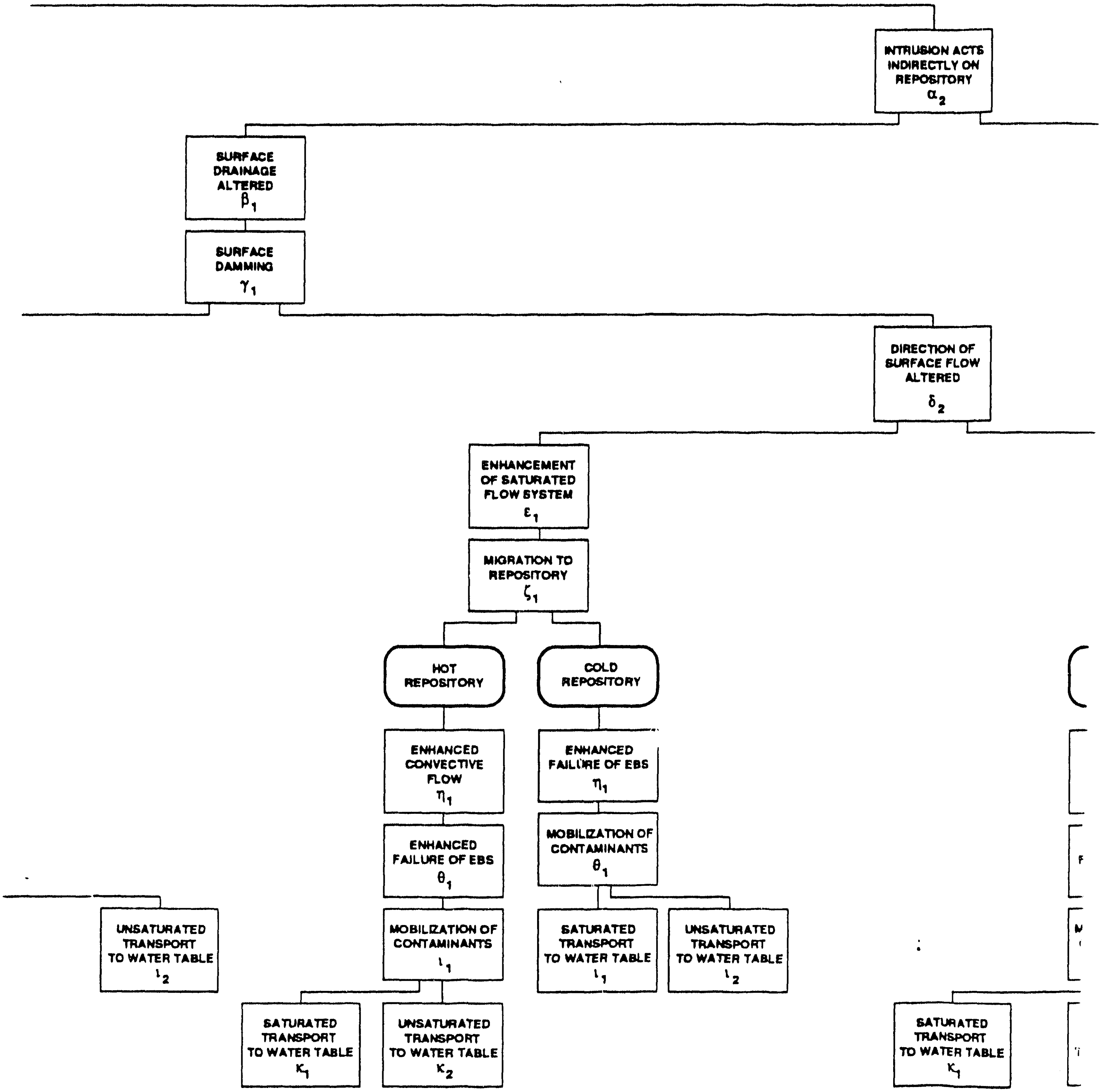
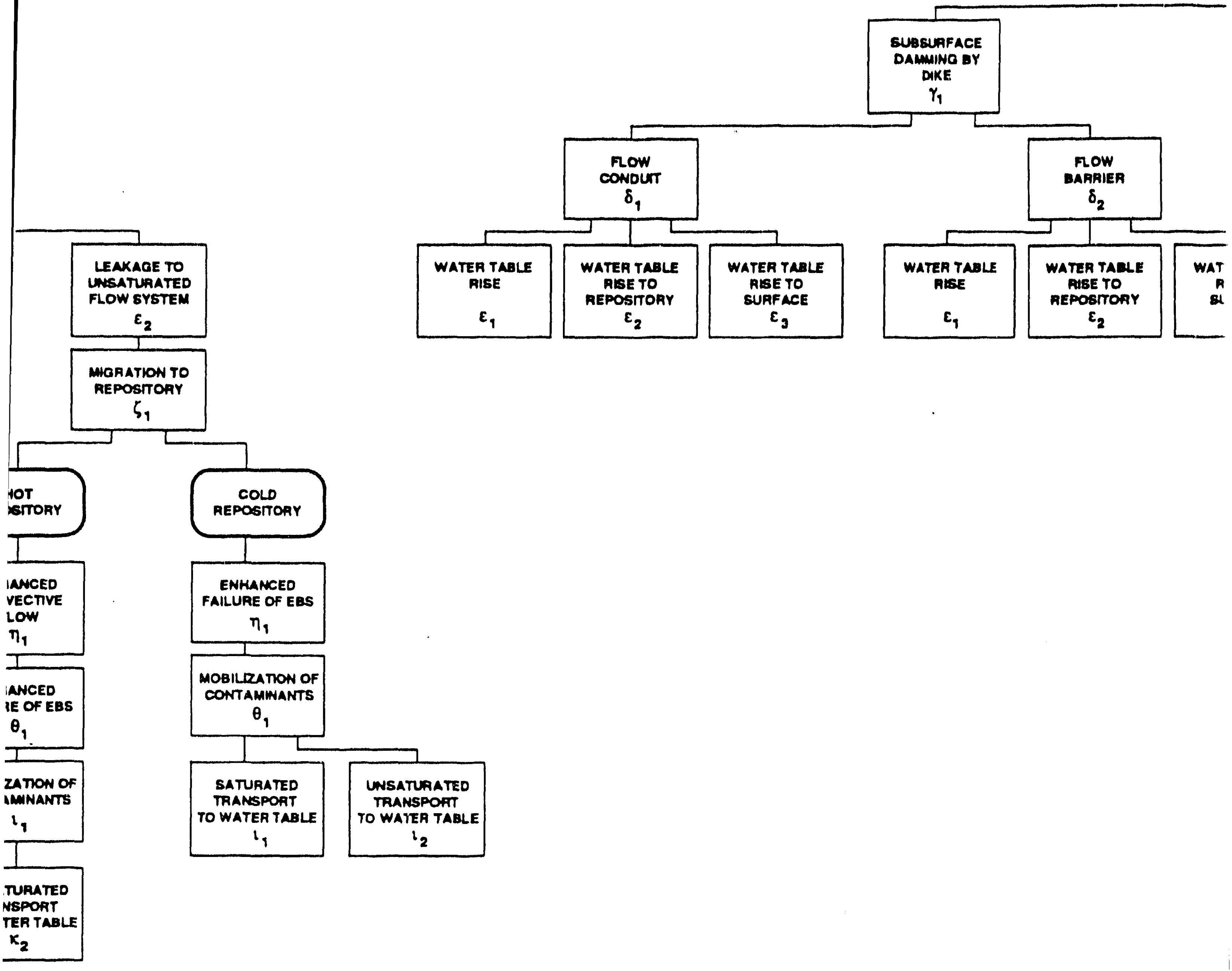
PORT IN URATED TEM TO R TABLE λ_2


INTRUSION ACTS INDIRECTLY ON REPOSITORY α_2
SURFACE DRAINAGE ALTERED β_1
SURFACE DAMMING γ_1
DIRECTION OF SURFACE FLOW ALTERED δ_2
ENHANCEMENT OF SATURATED FLOW SYSTEM ε_1
MIGRATION TO REPOSITORY ζ_1
HOT REPOSITORY
COLD REPOSITORY
ENHANCED CONVECTIVE FLOW η_1
ENHANCED FAILURE OF EBS θ_1
MOBILIZATION OF CONTAMINANTS ι_1
ENHANCED FAILURE OF EBS η_1
MOBILIZATION OF CONTAMINANTS θ_1
UNSATURATED TRANSPORT TO WATER TABLE ι_2
SATURATED TRANSPORT TO WATER TABLE κ_1
UNSATURATED TRANSPORT TO WATER TABLE κ_2
SATURATED TRANSPORT TO WATER TABLE ι_1
UNSATURATED TRANSPORT TO WATER TABLE ι_2
SATURATED TRANSPORT TO WATER TABLE κ_1


SUBSURFACE DAMMING BY DIKE
γ1
FLOW CONDUIT
δ1
FLOW BARRIER
δ2
LEAKAGE TO UNSATURATED FLOW SYSTEM
ε2
WATER TABLE RISE
ε1
WATER TABLE RISE TO REPOSITORY
ε2
WATER TABLE RISE TO SURFACE
ε3
WATER TABLE RISE
ε1
WATER TABLE RISE TO REPOSITORY
ε2
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SU
MIGRATION TO REPOSITORY
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OSITORY
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ENHANCED FAILURE OF EBS
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MOBILIZATION OF CONTAMINANTS
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ZATION OF
AMINANTS
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SATURATED TRANSPORT TO WATER TABLE
ι1
UNSATURATED TRANSPORT TO WATER TABLE
ι2
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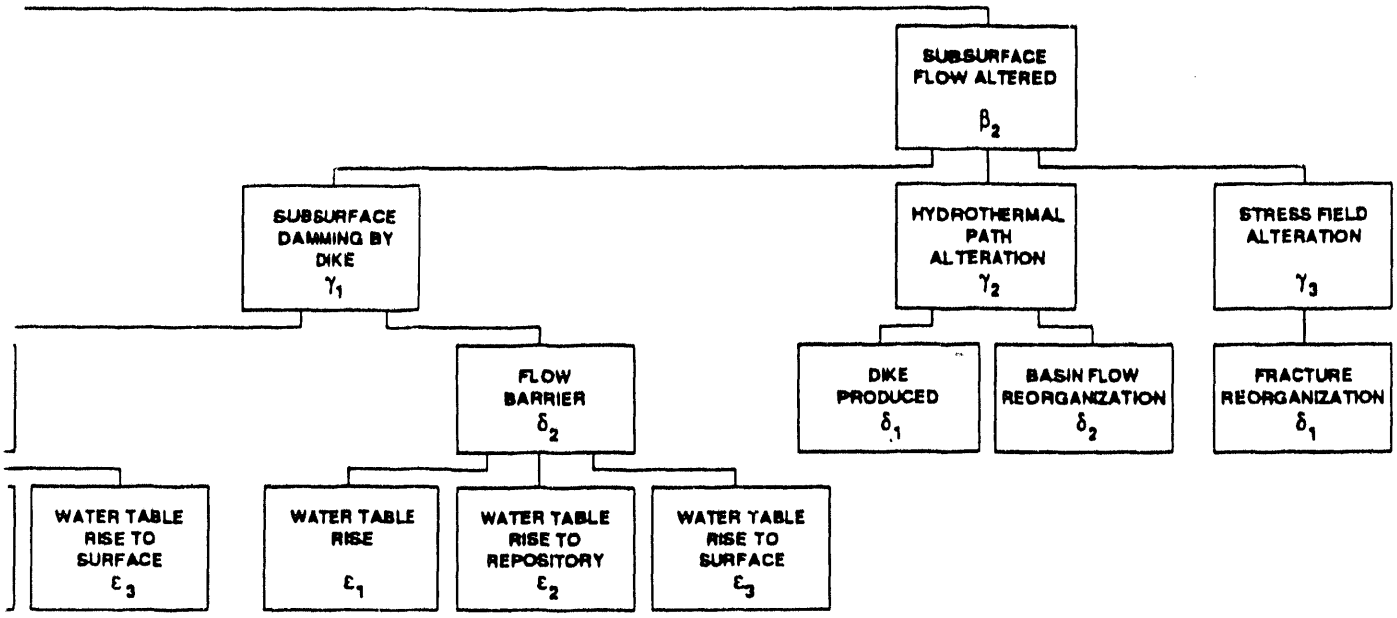
SUBSURFACE FLOW ALTERED β_2
SUBSURFACE DAMMING BY DIKE γ_1
HYDROTHERMAL PATH ALTERATION γ_2
STRESS FIELD ALTERATION γ_3
FLOW BARRIER δ_2
DIKE PRODUCED δ_1
BASIN FLOW REORGANIZATION δ_2
FRACTURE REORGANIZATION δ_1
WATER TABLE RISE TO SURFACE ε_3
WATER TABLE RISE ε_1
WATER TABLE RISE TO REPOSITORY ε_2
WATER TABLE RISE TO SURFACE ε_3

END

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