GEOMETRIC ANALYSES OF ALTERNATIVE MODELS OF TECTONIC FAULTING AT YUCCA MOUNTAIN

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1 INTRODUCTION

Yucca Mountain, Nevada is the potential site for a geological repository of high-level radioactive waste (HLW). Alternative models of tectonic deformation, specifically including models of faults and faulting, are expected to be used by the U.S. Department of Energy (DOE) to fulfill part of the requirement of 10 CFR Part 60 to describe and assess subsurface conditions, and to evaluate conditions that may be potentially favorable or adverse to effective waste isolation.

Under siting criteria presented in 10 CFR 60.122, structural deformation such as uplift, subsidence, folding, and faulting during the Quaternary Period [1.64 million years ago through the present (Harland et al., 1990)], if characteristic of the controlled area or if it could affect isolation within the controlled area, is specifically included as a potentially adverse condition in 10 CFR 60.122(c)(11). NRC staff have previously determined that 2 million years is an appropriate time span for considertaion of these processes. In 10 CFR 60.122(C)(4), structural deformation, such as uplift, subsidence, folding, or faulting that may adversely effect the regional groundwater flow system is considered as a potentially adverse condition. Earthquakes which have occurred historically, that if they were to be repeated could affect the site significantly [10 CFR 60.122(c)(12)], and indication, based on correlations of earthquakes with tectonic processes and features, that either the frequency of occurrence or magnitude of earthquakes may increase [10 CFR 60.122(c)(13)] require assessment as potentially adverse conditions. Earthquake activity that may occur more frequently, or with higher magnitude than is typical of the area in which the geologic setting is located [10 CFR 60.122(c)(14)], would require assessment as a potentially adverse condition if determined to be characteristic of the controlled area, or if it may affect isolation in the controlled area.

As indicated by 10 CFR 60.122(a)(2)(i) - (iii), the following must be demonstrated to show that a potentially adverse condition does not compromise performance of the repository: (i) the condition has been adequately investigated, (ii) the condition has been adequately evaluated using analyses sensitive to the condition and assumptions which are unlikely to underestimate its affects, and (iii) the condition is shown by analysis not to significantly affect waste isolation, be compensated by favorable characteristics or be mitigated.

In 10 CFR 60.21(a), a Safety Analysis Report is required as part of the license application. The Safety Analysis Report shall include a description and assessment of the site at which the proposed geologic repository operations area is to be located with appropriate attention to those features of the site that might affect geologic repository operations area design and performance [60.21(c)(1)]. Where subsurface conditions outside the controlled area may affect isolation within the controlled area, the description must include such information with respect to subsurface conditions outside the controlled area to the extent such information is relevant and material [10 CFR 60.21(c)(1)(i)]. The required detailed information shall include the orientation, distribution, aperture in-filling and origin of fractures, discontinuities, and heterogeneities; the presence and characteristics of other potential pathways such as solution features, breccia pipes, or other potentially permeable features; and the geomechanical properties and conditions, including pore pressure and ambient stress conditions [10 CFR 60.21(c)(1)(i)(A)(B)and(C)]. The required assessment, as described in 10 CFR 60.21(c)(1)(ii)(A)-(F), should include analysis of the geology, geophysics and hydrogeology; and analyses and evaluations of favorable and potentially adverse conditions, post-closure performance, and the effectiveness of natural barriers.

Content requirements for the Safety Analysis Report, reliable estimation of probabilities of occurence and assessment of engineering effect of tectonic processes and events at Yucca Mountain will depend on geological models of subsurface fault shape. Effective assessments of risk due to geologic hazards such as fault rupture, earthquake seismicity, and volcanic eruptions will involve the use of tectonic and structural geologic models of Yucca Mountain. Estimation of the effects of fault movement and associated distributed deformation on fracture patterns, and potential concomitant changes in bulk hydrogeologic properties, require knowledge of fault geometry and displacement. Yucca Mountain is located in a tectonically active region, and has a recent geological history of normal fault deformation. To date, results of site characterization activities useful in structural geological description and interpretation of the Yucca Mountain area have been presented primarily as geological maps and cross sections. This report reviews established and new applications of existing methods to development and assessment of alternative models of tectonic faulting at Yucca Mountain. The approach used is focused on application of two classes of constraints to either build tectonic models from basic data, or substantially restrict the field of applicable models from a broader suite of alternatives. Models of tectonic faulting and associated hangingwall deformation are developed and evaluated on the basis of (i) deformation mechanism, and (ii) structural style as discernable within the geologic setting.

1.1 MECHANISM-DRIVEN MODELS

Two basic types of geological cross-sections exist for Yucca Mountain. The first type are descriptive geological sections. These include either strictly conceptual models of fault geometry (Fox and Carr 1989) in the deep (> 1000 m) subsurface, or are accurate depictions of field-derived data but do not extend beyond about 1000 m below the surface (Scott and Bonk, 1984). In either case, these sections usually make no attempt to provide an integrated, mechanistic interpretation of geological structures. The second kind (Young et al., 1991) are based on the first as a data source but attempt to integrate all currently available geological and geophysical information into interpretations that incorporate fault shapes that are capable of generating the observed geological structures, assuming that certain deformation mechanisms have been operative. These second kinds of sections can reasonably be called "second generation" sections.

Thus far, second generation sections have been confined to the assumption of vertical shear as the dominant deformation mechanism. However, a number of other mechanisms can be invoked and may provide, if not complete solutions, some insight into the range of interpretations that can be applied to Yucca Mountain. The purpose of this report is to outline the range of deformation models that can be applied to Yucca Mountain, explain the salient points of each, and examine the applicability of the models to the Yucca Mountain area.

Published models of hangingwall faulting deformation are discussed and examined in the light of potential applicability to Yucca Mountain. Two criteria are used to test the utility of each of the specific deformation models. First, can the model explain the known surface geological features as mapped and described by Scott and Bonk (1984) and Scott (1990); and second, can the model provide a cross-section interpretation that is "geologically balanced and restorable"?

1.2 CONTEXT-DRIVEN MODELS

In order to construct a reasonable cross-section, it is necessary to have a grasp of the geological context in which the problem exists. An understanding of the geological context is at least as important as choosing the appropriate deformation mechanism(s) to describe the deformed state of the region of interest. For example, in the offshore Gulf of Mexico region, the overwhelming bulk of data indicates the presence of listric normal faults and the applicability of inclined or vertical shear to describe the extension in the post-rift sedimentary sequence (Dula, 1991); the huge thickness of this post-rift sequence reduces the effects of the syn-rifting tectonic style almost to zero when considering the overall tectonic style (Figure 1-1; Bally, 1983). In contrast, the Gulf of Suez and the Paleozoic basins distributed along the eastern and southern margin of the North American continent show evidence of interaction between two distinct styles of tectonism (Figure 1-2).

Use of any specific type of structure (e.g. faults and folds), or process of deformation (faulting and folding) in a structural geologic cross section should be consistent with the observed tectonic style and evolution of the regional geologic setting. In the Gulf of Mexico example noted above, cross sections constructed strictly with planar faults would be in violation of a key set of data (reflection seismic), or view of the region, indicating that the faults are curved. Such a section would be considered less plausible than a section that included the listric fault geometries. In essence, structural styles used to construct cross sections should be characteristic of the region and compatible with the total body of geologic data. Cross sections that include unique features, not otherwise discernable within the region require special explanation of those particular features. Dahlstrom (1969) suggests that only structures observable within the pertinent geologic setting are generally permissable for inclusion on cross sections.

Although mechanism- and context-driven models are not independent of each other, they do derive from different views of the data. An understanding of deformation mechanisms and their

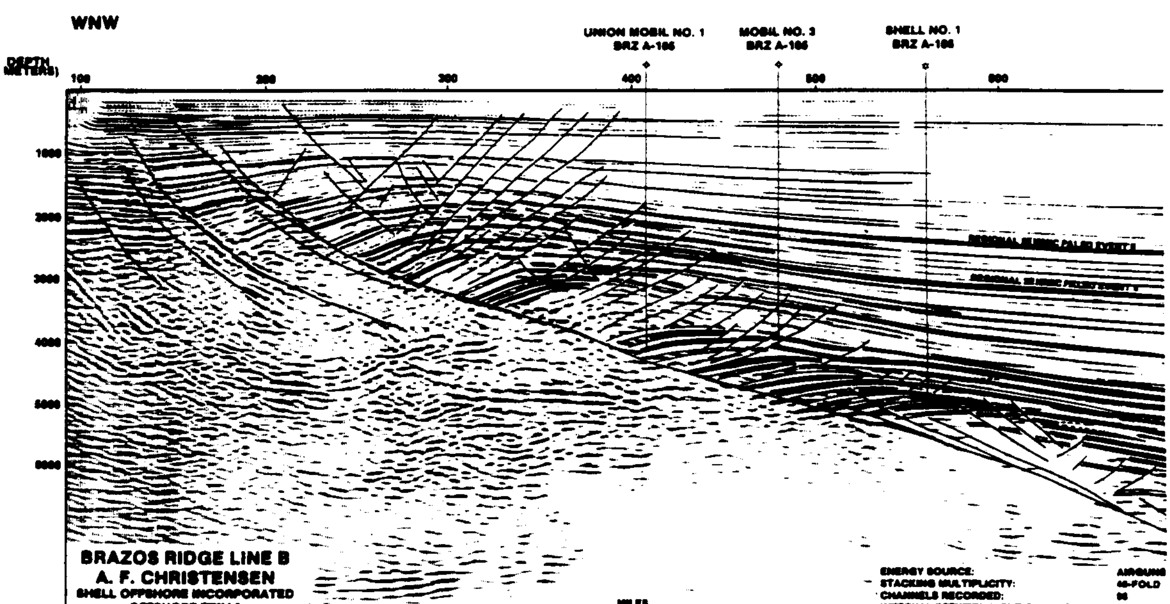


Figure 1-1. An example of listric faulting and the dominance of vertical/oblique shear in post-rift sediments from the Gulf of Mexico (from Bally, 1983). Vertical scale is depth (meters).

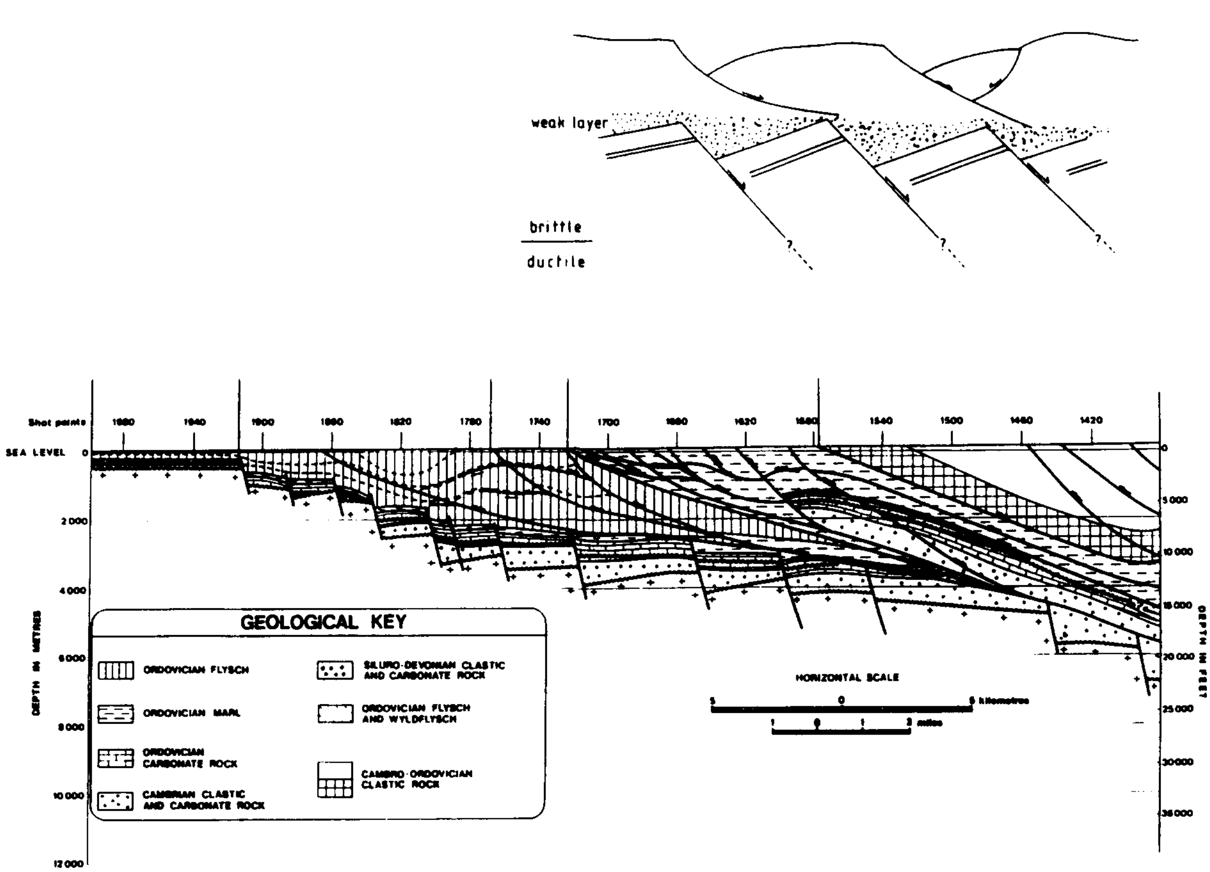


Figure 1-2. The upper figure is a schematic representation of shallow, weak sediments detaching into listric faults above more rigid domino block style basement faulting (Jackson et al, 1988). The lower figure is an example of this tectonic style from Quebec (Bally, 1983).

significance is necessary in order to evaluate and "tune" context-driven models of regional deformation. Consequently, this report deals first with mechanisms and secondly with context-driven models of deformation that may be applicable to Yucca Mountain.

2 MECHANISM-DRIVEN MODELS

2.1 BALANCE AND RESTORABILITY

Geological cross-sections of deformed terrains are drawn using a variety of input data, including, surface geology, seismic reflection and refraction information, and well data. These windows of reality leave large portions of the section to the geologist's imagination. Reliance upon cross-sectional interpretations in the petroleum exploration of the Canadian Rocky Mountain foothills during the 1950s led geologists to formulate geometric rules to apply to the interpretation of blank areas on their sections. Dahlstrom's classic 1969 paper is often referred to as a milestone in this thought process.

For a deformed-state geological cross-section to be realistic (i.e., a credible approximation to reality) it must be balanced or restorable to an undeformed state that is geologically reasonable. This philosophical constraint reduces the range of interpretations but does not necessarily provide a unique solution.

In practice, the restorability or otherwise of a cross-section is established using the principle of conservation of material, which for a two-dimensional representation of geological structures requires that the cross-section plane contain the relative movement vector(s) of the features being depicted and that the deformed and restored states must have equal areas ("area-balanced"). Departures from this principle frequently occur but must be accounted for by geologically reasonable processes. For example, in areas of extensional deformation, deposition may be synchronous with fault movement (so-called "growth" faults); as faulting and sediment accumulation proceed, the sediment is progressively compacted as it is buried more deeply. When restoring a section drawn through such structures, it is necessary to account for this change in the cross-sectional area by decompacting each sedimentary layer sequentially according to its lithological character (Sclater and Christie, 1980; Baldwin and Butler, 1985).

Within the last ten years, the principle of restorability has been taken a step further to encompass the idea of retrodeformability. This has grown out of an improved understanding of the mechanisms by which rocks deform. It is no longer sufficient that a section be area-balanced, but it must be shown that the geometries in the deformed state can have developed from the restored state by the application of kinematically viable deformation mechanisms. The range of acceptable interpretations of the data is further narrowed by this additional constraint.

A balanced, or restorable, cross-section can be arrived at in a number of ways, and confidence in the interpretation will be greater if it is retrodeformable rather than merely restorable. Cross sections can be directly constructed, or forward modeled, to be perfectly retrodeformable. Existing sections can be examined for restorability, and modified within data constraints to be retrodeformable. However, central to the concept of retrodeformability is some knowledge of the mechanism or mechanisms by which the area under consideration deformed. The assumed means of deformation must pass two tests: (i) it can generate the known characteristics of the current geology and (ii) it is geologically feasible given the known history of the area. In addition, any geological cross-section that purports to be "balanced" must be accompanied by an explanation of the method(s) that were used to establish balance.

2.1.1 Restorability

A balanced section, whatever the means by which it was produced, is not necessarily truth; it is, however, more believable than a nonbalanced section, and all geological cross-sections should be examined with the concept of balance in mind. The following procedures can be used to quickly check the general restorability of a cross section tectonic model by examination.

- Hangingwall and footwall cutoff templates (patterns) must be topologically compatible (i.e., the number and order of geological horizons cut by the fault in the hangingwall must match those in the footwall) (see, for example, Figure 2-1).

- Displacements of geological horizons along faults should be compatible with each other. In the simplest case, a normal (extensional) fault should have normal (extensional)

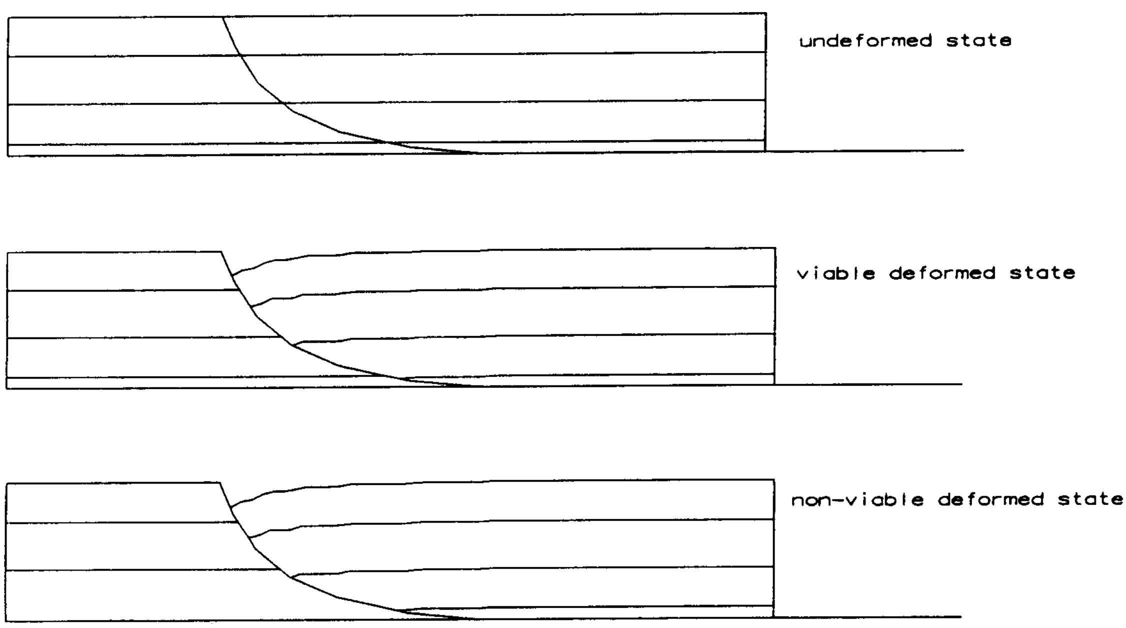


Figure 2-1. Hangingwall and footwall cutoff patterns must be topologically compatible. By tracing along the fault, the hangingwall of the viable deformed state has the same number of geological horizons, in the same order as the footwall. This is not the case for the nonviable deformed state; the hangingwall has one extra horizon in comparison with the footwall.

displacements all along its trace. If the fault is planar, the amount of displacement should be constant along the fault; if the fault curvature varies monotonically with depth, then the displacement should also vary monotonically with depth. For sections in which all slip within the hangingwall is assumed to occur parallel to the fault, displacement should not vary along the fault trajectory. These simple rules apply provided there has not been a complex history of syn-deformational deposition, and/or uplift. Further, these rules do not apply simply to faults that have experienced reversal (inversion) of displacement sense. An example of incompatible displacements is shown in Figure 2-2.

- The domino block-rotation (planar fault) deformation model requires that all fault blocks in the section have the same dip (Figure 2-3; Axen, 1988). Dips that vary from block to block within the section would imply that different blocks had rotated by different amounts, and this causes the section to be unrestorable by the domino method. Hybrid models (see below) permit dip variations at block margins, but the interiors of blocks will still conform to this rule.

2.2 VERTICAL/OBLIQUE SHEAR

Distributed vertical simple shear and oblique simple shear are deformation mechanisms that have been applied to extensional structures in the Gulf of Mexico with a great deal of success (e.g., Dula, 1991). As the crust is extended, listric normal faults develop that dip steeply near the surface and become progressively less steep with depth, often "soling" into a sub-horizontal zone of relatively localized ductile deformation (detachment fault zone), such as shale or evaporitie beds. Within extended terrains that involve highly indurated (hard) rocks with well developed layering, the detachment zone, or fault, may occur within ductile strata, such as shale or salt, or at discrete mechanical-stratigraphic contacts of comparatively low frictional resistance. For example, experimentally determined frictional coefficients for limestone-limestone and dolomite-limestone contacts are substantially higher than for dolomite sliding on dolomite (Stearns et al. 1981; Logan et al. 1972). The hangingwall block, as it moves over the fault surface, maintains contact with the fault by internal collapse. This collapse is accommodated by uniformly distributed slip on closely-spaced vertical or inclined shear planes (Figure 2-4) as if the hangingwall were composed of a deck of cards with a consistent orientation. In reality, these shear planes may be manifest as quasi-pervasive fault systems or as arrays of synthetic and antithetic faults within the hangingwall (Figure 2-5). Fault trajectories modeled using generalized simple shear are balanced solutions; that is, the deformed-state hangingwall used to construct the fault will restore to a balanced undeformed state.

2.2.1 Key Characteristics of Vertical/Oblique Shear Models

Geometric models of deformation produced using generalized vertical/oblique simple shear as the deformation mechanism have the following characteristics:

- Well-developed rollover geometry
- Listric fault geometry that corresponds with rollover geometry
- Development of deformation fabric in hangingwall consistent with deformation mechanism.

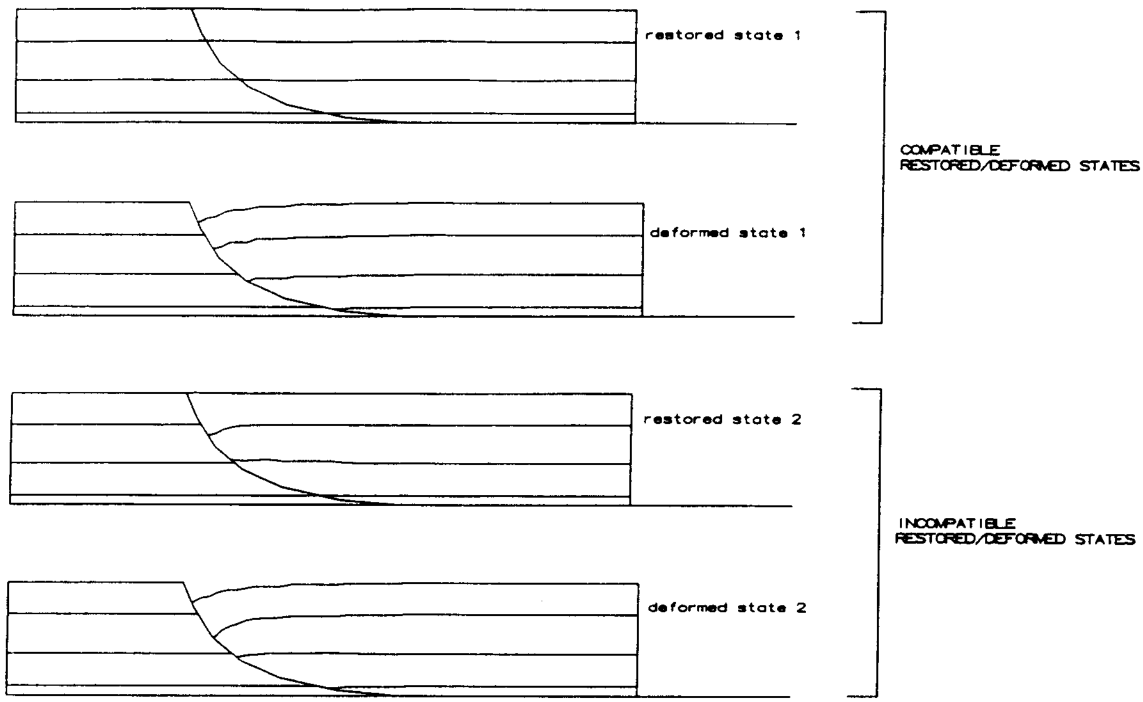


Figure 2-2. Incompatible displacements: the curvature of the fault illustrated varies monotonically with depth, and thus, displacements of the geological horizons cut by it should either be constant (if all hangingwall slip is parallel to the fault) or vary monotonically. In the second example shown, displacement varies nonmonotonically with depth, and therefore, this is not a viable section.

2.2.2 Applicability of Vertical/Oblique Shear to Yucca Mountain

Thus far, all second generation cross-sections of Yucca Mountain have invoked vertical shear (Young et al., 1991; Young et al., 1992). The primary reasons for choosing this mechanism are the occurrence within the hangingwalls of the major Yucca Mountain faults of networks of subvertical, small-displacement faults (Scott, 1990), and the ability of this method to explain true rollover (increasing counter-dip) into the major fault zones, as documented by Scott and Bonk (1984). Published models of vertical/oblique shear deformation known to the authors require that hangingwall rollover folds occur over curved faults, and conversely, that curved faults result in rollover folds.

2.3 FLEXURAL SLIP

Layering in some form is the most common primary anisotropy in rocks. Sedimentary and volcanic rocks are particularly exemplary of this, dominated as they are by bedding, flow lamination, or structural (mechanical) stratigraphy imparted by vertical welding and compaction gradients within ash flow cooling units. Lithological layering is (almost invariably) a mechanical anisotropy which strongly

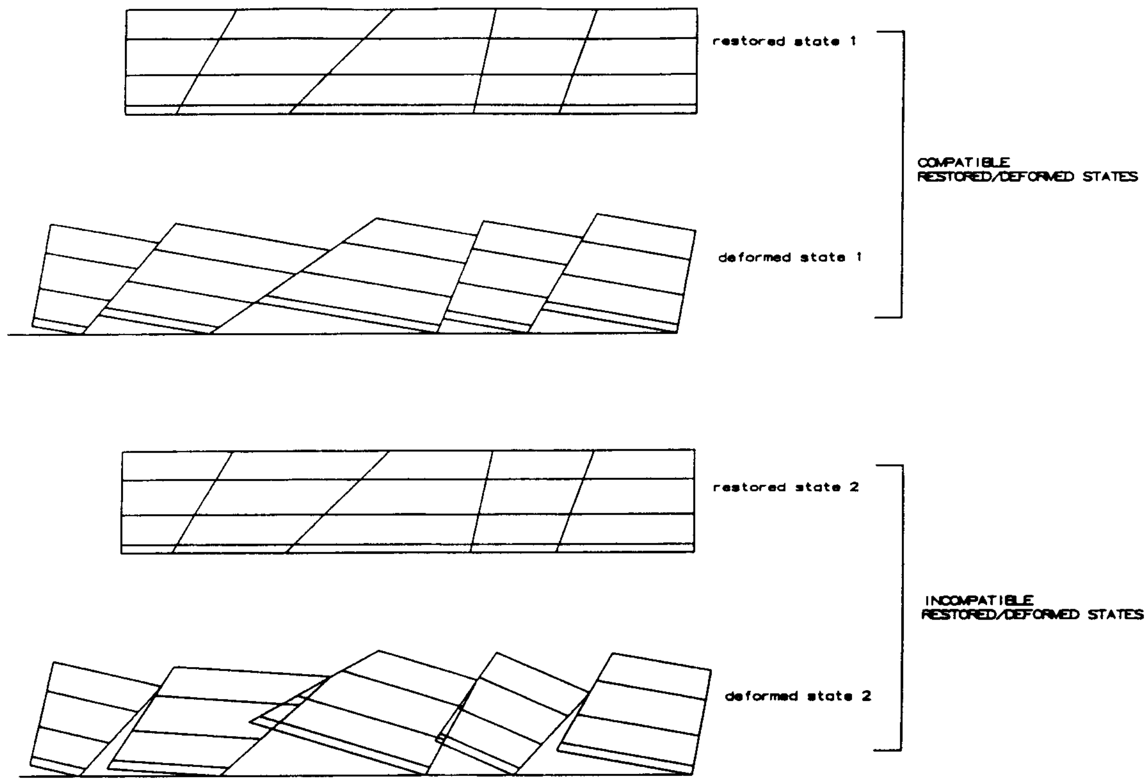


Figure 2-3. Domino block deformation requires that fault blocks must have the same dip, or unacceptable "space problems" occur.

influences deformation behavior of the layered sequence. This is especially true for contractional deformation but may also apply to certain instances of extension. Because the layers represent mechanically homogeneous units, large scale shape changes are accommodated by sliding between layers (the bending telephone directory analogue). This is flexural slip. Flexural slip can also occur by more pervasive slip within units but still along discrete surfaces parallel to layering. In the case of an extensional listric fault (Figure 2-6), hangingwall collapse is accommodated by bending of the layers within the hangingwall block, and this bending is in turn accommodated by layer-parallel slip. This is not a mechanism that is often invoked to explain hangingwall deformation above normal faults, but it has been considered (Groshong, 1989; Higgs et al., 1991; Dula, 1991).

2.3.1 Key Characteristics of Flexural Slip Models

Geometric models of deformation produced using a flexural slip/flow deformation mechanism have the following characteristics:

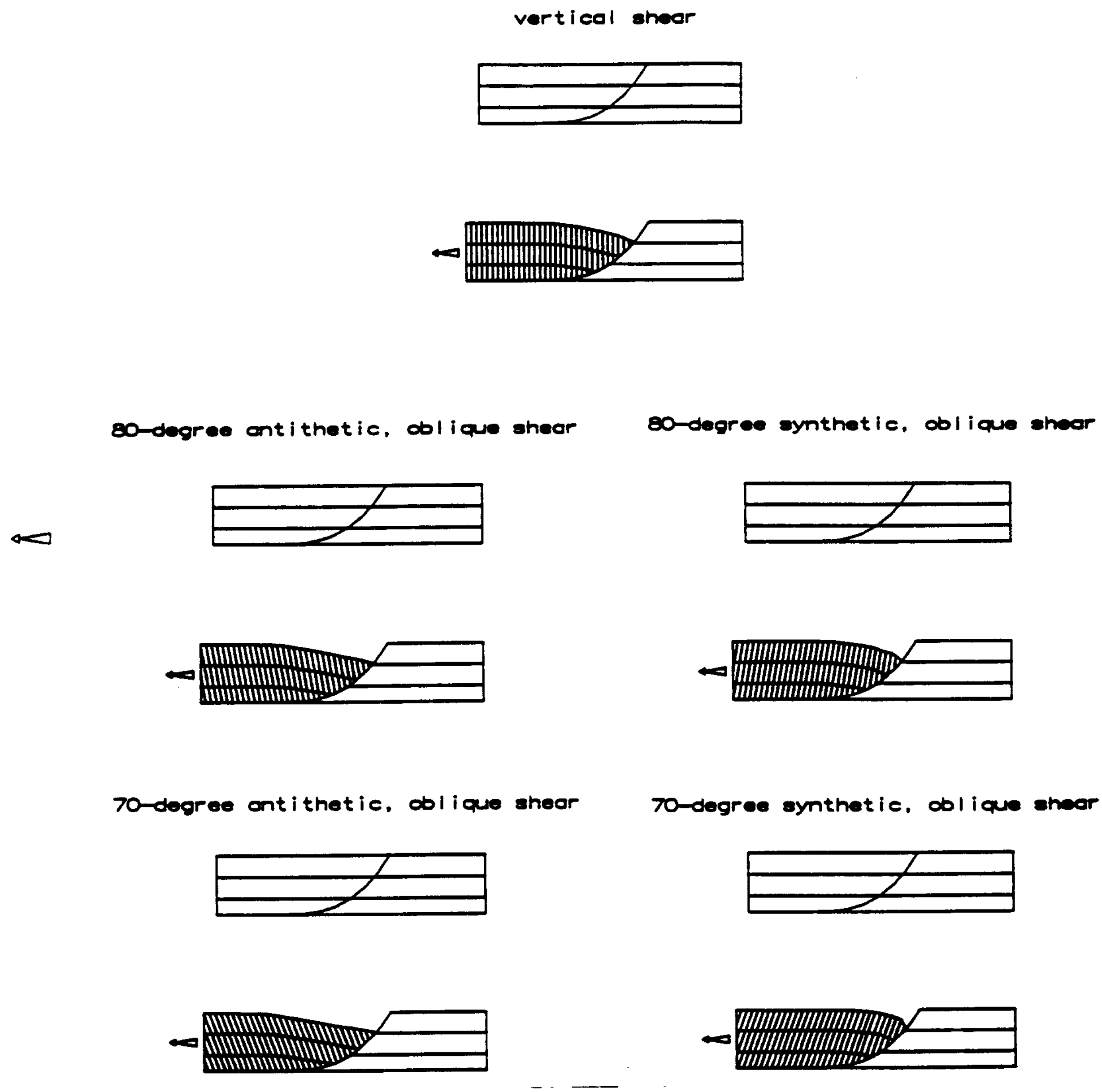


Figure 2-4. Undeformed and deformed states based on the same listric fault but employing different shear angles. Closely-spaced vertical/inclined ruling illustrates geometry and distribution of slip surfaces within hangingwall block.

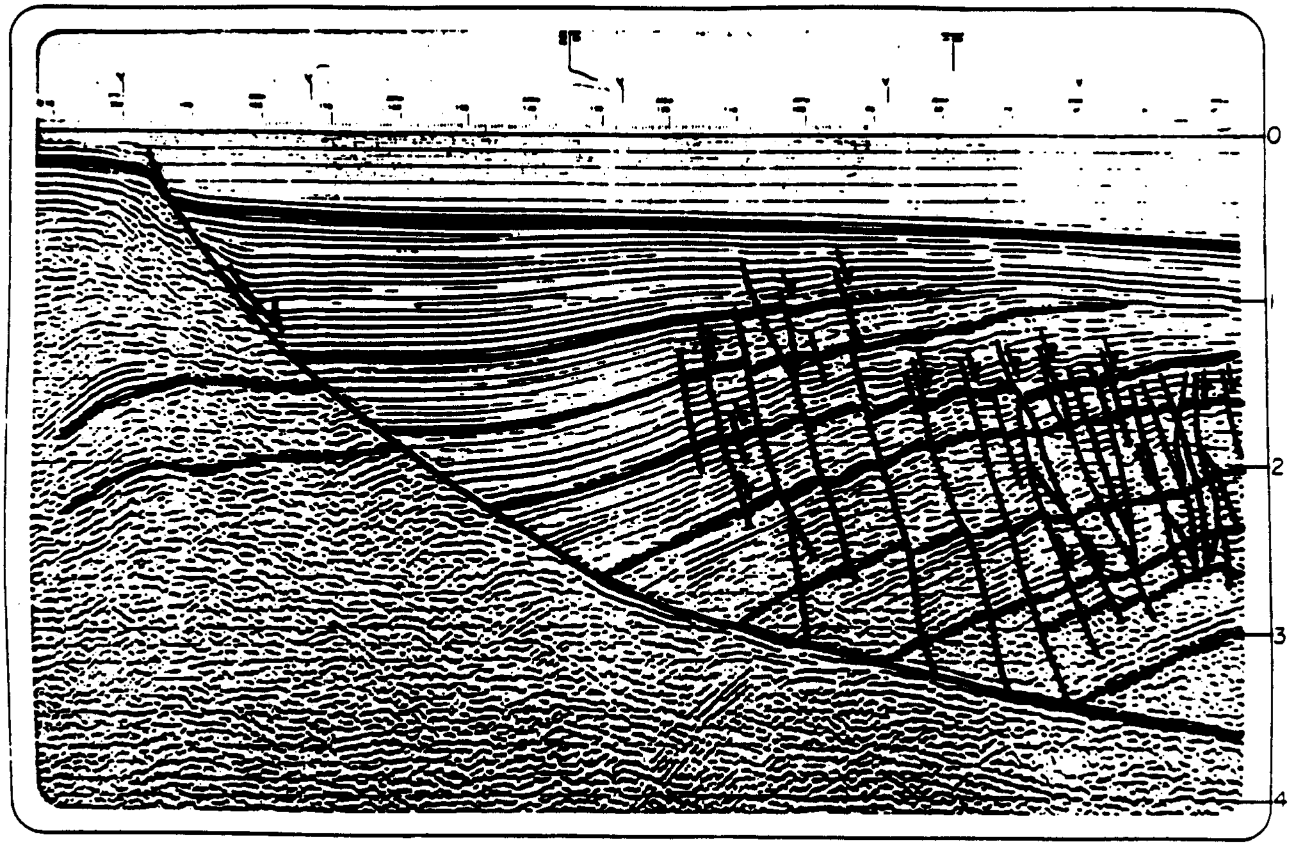


Figure 2-5. Reflection seismic record section of extensional structure below continental shelf of Gulf of Mexico. Listric normal fault with well-developed fabric of contributory faults in the hangingwall (Wernicke and Burchfiel, 1982). Vertical scale is in 2-way travel-time.

- Well-developed rollover geometry
- Listric fault shape that corresponds with rollover geometry
- Development of deformation features in hangingwall that are consistent with flexural slip.

2.3.2 Applicability of Flexural Slip to Yucca Mountain

Flexural slip solutions for the major faults at Yucca Mountain (Fortymile Wash, Paintbrush Canyon, Midway Valley, Bow Ridge, Solitario Canyon, Fatigue Wash) yield similar depths-to-detachment as the vertical shear models but slightly different fault trajectories when examined in detail (Young et al.,

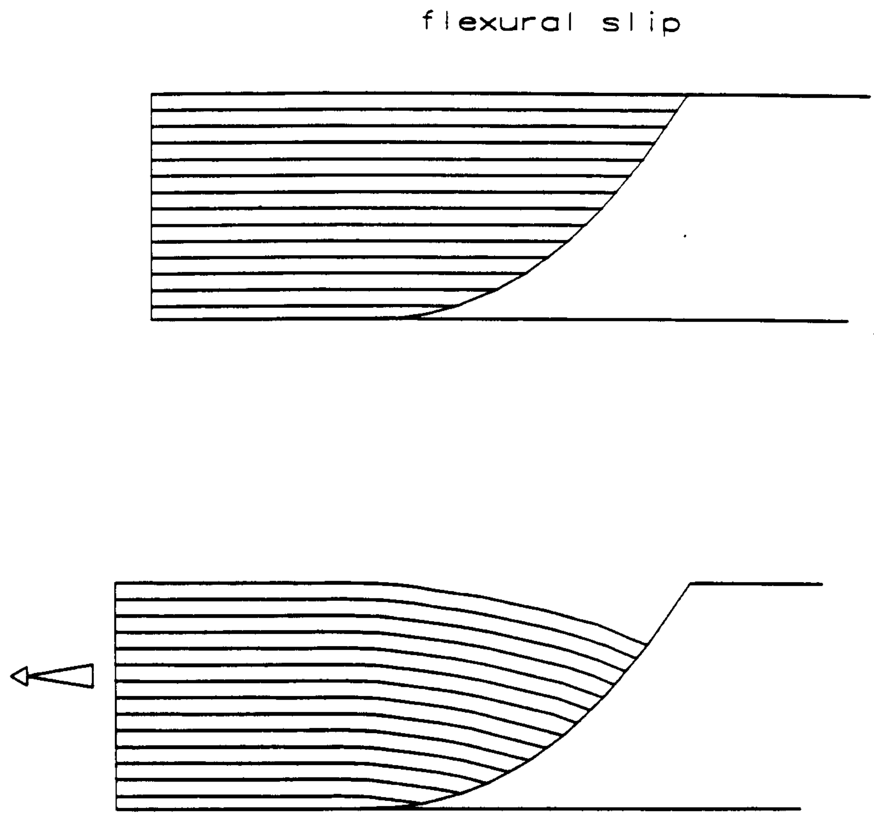


Figure 2-6. Rollover above a listric normal fault produced by flexural slip in the hangingwall and with zero shear at the leading (in this case, the left) edge of the hangingwall block

992). In terms of geometry, flexural slip can provide reasonable cross-sectional interpretations of Yucca Mountain. The primary question concerning this mechanism is: Is it reasonable to expect flexural slip to have occurred in the hangingwall blocks of Yucca Mountain faults? The currently available geological data do not permit this mechanism to be ruled out, although there is no strong evidence for it. Indicators of layer-parallel shear (e.g., slickensides or shear zones) have not been documented within the ash flow tuff sequences at Yucca Mountain, and structural complexity within the well layered Paleozoic and late Proterozoic sedimentary rocks below the volcanics would probably preclude bedding orientations favorable for flexural slip compatible with the late Cenozoic extensional fault system.

2.4 SLIP-LINE

Slip-line deformation of hangingwalls above listric faults is perhaps the most intuitively satisfying of the commonly proposed mechanisms. All particles within the hangingwall are considered to move along pathways that are parallel to the (projected) geometry of the fault (Figure 2-7). Recent analogue modelling with elay (Dula, 1991) has shown that hangingwall particle trajectories above an active listric normal fault closely approximate slip-line deformation when viewed from the reference framework of the (undeformed) footwall. Despite this observation in the modelling, Dula concluded that slip-line deformation is not applicable because it consistently underestimates depth to fault when used to predict fault shapes. This is probably due to an error in the construction technique used by Dula which incorrectly constructs the particle trajectories from the fault geometry. For his examples, slip-line deformation provides an excellent fit between his known hangingwall and fault shapes (Figure 2-8).

2.4.1 Key Characteristics of Slip-Line Models

Geometric models of deformation produced using a slip-line deformation mechanism have the following characteristics:

- Well-developed rollover geometry
- Listric fault shape that corresponds with rollover
- Development of deformation features in hangingwall that are consistent with slip-line deformation.

2.4.2 Applicability of Slip-Line Models to Yucca Mountain

Figure 2-9 shows that slip-line deformation can generate a close approximation to the observed geometry of the top of the Topopah Springs Member of the Paintbrush Tuff (Tptw) at Yucca Mountain. There are no geometrical objections to the use of this deformation mechanism; however, it does imply a degree of ductility throughout the hangingwall for which there is no direct geological evidence.

2.5 DOMINO

The tendency for deforming crust to behave as rigid or semi-rigid blocks has been recognized in a number of tectonic settings, notably in regions where extensional tectonism involves primarily well indurated sedimentary rocks effectively coupled to a thick underlying crystalline structural basement (i.e. a thick brittle upper and middle crust section). Deformation in such a setting has been described in terms of "domino" blocks. Each block undergoes a rotation, and faults are either planar or arcs of circles (Figure 2-10; Axen, 1988; Davison 1989). Space "problems" at the bases of the domino blocks are considered to be accommodated by brecciation or by ductile, aseismic flow at some appropriate level in the crust.

2.5.1 Key Characteristics of Domino Models

Geometric models of deformation produced using a domino-block deformation mechanism have the following characteristics:

- Consistent dips from block to block

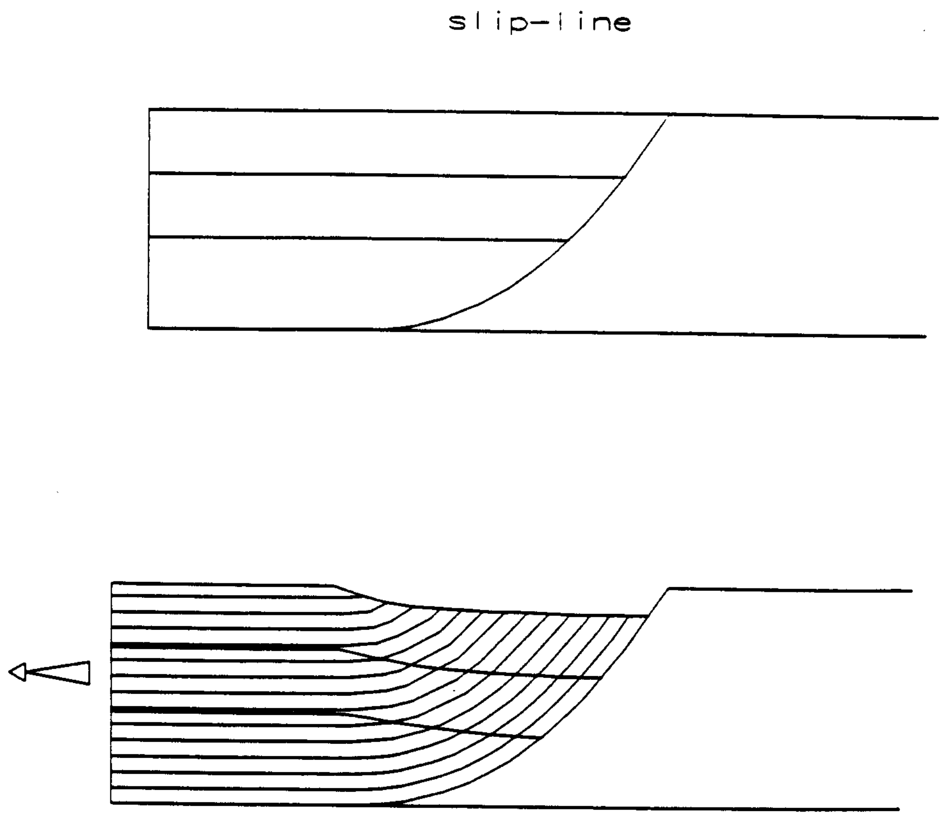


Figure 2-7. **Rollover above a listric normal fault produced by slip in the hangingwall along surfaces parallel to the fault. In this construction, for conservation of area and zero shear at the leading (in this case left) edge, the particle trajectories are computed to the projected, parallel geometry of the fault surface. This is significantly different from the construction used by Dula (1991) and Williams and Vann (1987) which loses area and generates incorrect hangingwall geometries.**

- Little or no dip variation within blocks (i.e., no "rollover")
- Planar fault shapes
- It is geometrically necessary that all faults in a domino system are active synchronously (Axen, 1988; Davison, 1989).

2.5.2 Applicability of Domino Models to Yucca Mountain

It is possible to construct simple domino model interpretations for Yucca Mountain (Figure 2-11). Steepness (dip) of the principal faults increases with interpreted, or assumed depth to initial subhorizontal detachment at the brittle-ductile transition. Fault dip decreases eastward from the vertical

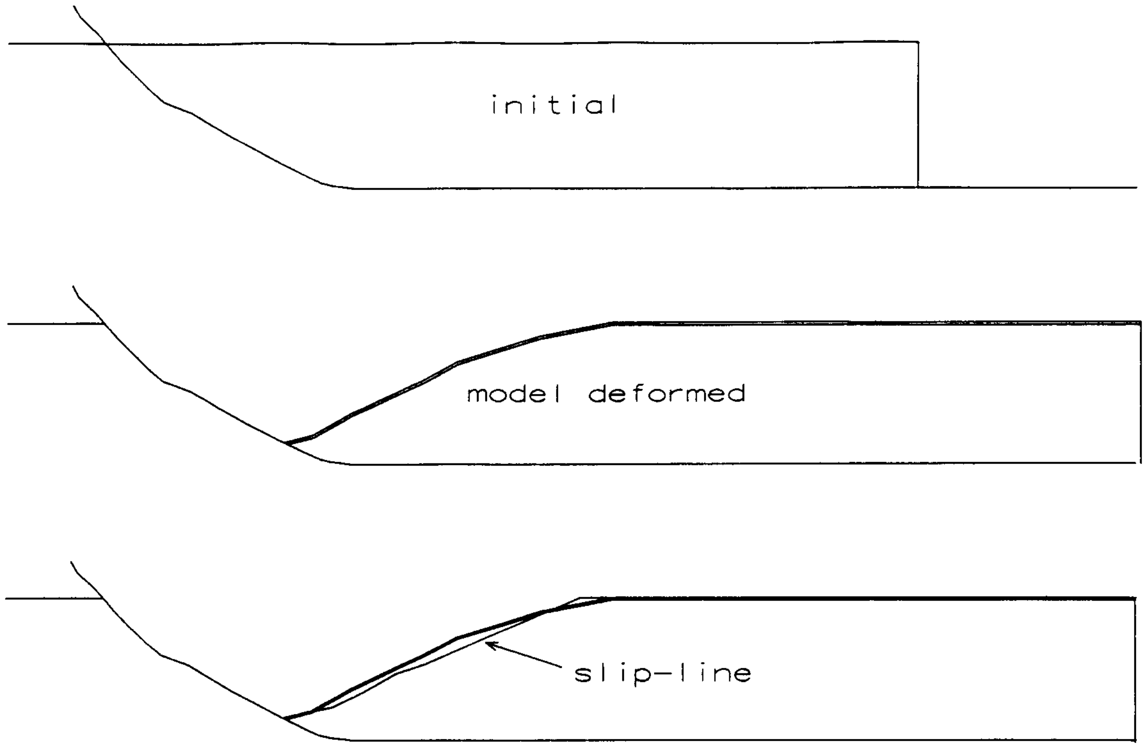


Figure 2-8. The top figure shows the undeformed state of Dula's clay model. The middle figure shows the actual deformed state of his model. The bottom figure superimposes the hangingwall geometry derived from the fault surface and slip-line deformation (as defined in this report).

reference pin (initial vertical reference line) at the west end of the model. It follows that fault dip can be tested for compatibility with estimates of depth to brittle-ductile transition made from geophysical data or from frequency-depth relationships of earthquake foci. Using the domino method of deformation modeling it is not possible to model "rollover" into the major fault zones, and it is necessary for all fault blocks to have the same dip (in the case of Figure 2-11 this dip is 6 degrees east).

Field data published by Scott and Bonk (1984) clearly show that different fault blocks have different dips and that there is well-developed "rollover" within each block; features inconsistent with domino deformation. Scott (1990) documents decreasing fault dip from north to south along the strike trend of the major bounding faults, with an average fault dip of about 66 degrees for the central and northern part of the fault system and 51 degrees in the southern part. Smith et al. (1989) have determined the depth to initial brittle-ductile transition to be about 15 - 20 km. Assuming constant fault block dips of 6 degrees, a 15km detachment zone requires that the major bounding faults have dips in excess of 75 to 85 degrees, substantially higher than average dips documented by Scott (1990). These observations cast doubt on the utility of simple domino models for Yucca Mountain. A final, powerful diagnostic test for the applicability of domino style faulting to Yucca Mountain may be provided by improved knowledge of the depositional history of the Tertiary pyroclastic sequence: the requirement that domino systems must

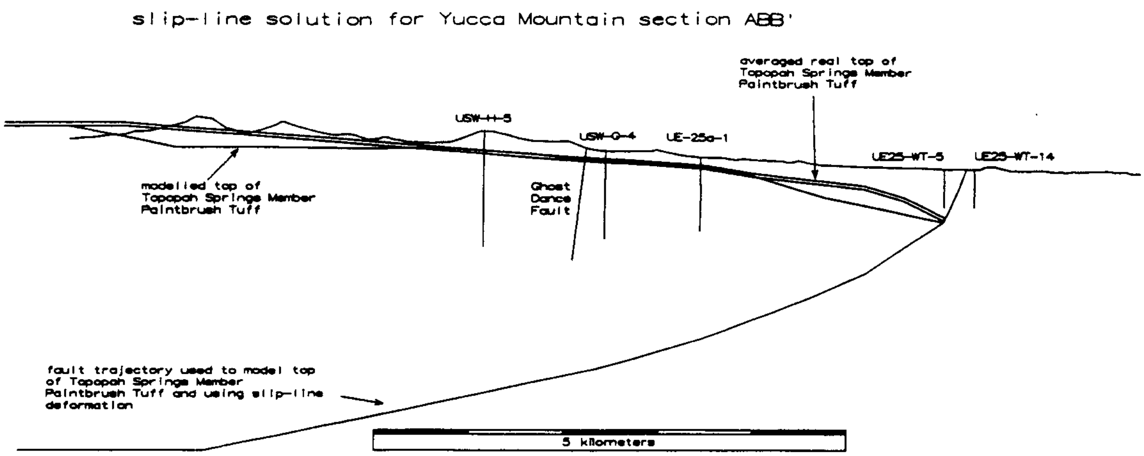


Figure 2-9. Slip-line model of the broad characteristics of the geometry of the top of the Topopah Springs Member of the Paintbrush Tuff. Modeled hangingwall horizon is retrodeformable. See Stirewalt et al. (in press) or Young et al. (1991) for index map of cross section locations.

have linked fault motion precludes the possibility of variable growth across the area; thus, if variable growth is observed, the domino model can be rejected.

2.6 HYBRID MODELS

The relative simplicity and elegance of the domino model has led to modifications of it to explain some common observations that cannot be generated by simple application of domino block deformation. Of particular interest is the observation of changing dips close to faults. One option is to treat most of the fault block as a rigid domino that experiences rigid-body rotation and translation, while near block edges heterogeneous simple shear accommodates some of the shape changes required to produce variable dips (e.g., Figures 2-12 and 2-13).

2.6.1 Key Characteristics of Hybrid Models

The principal fault blocks must have the same dip, although dips will vary into the fault zones. It is possible to generate "normal drag" in fault zones (bedding dips steeply in the same direction as the fault) using these methods, but it is not possible to produce a steepening of rollover as the fault is approached.

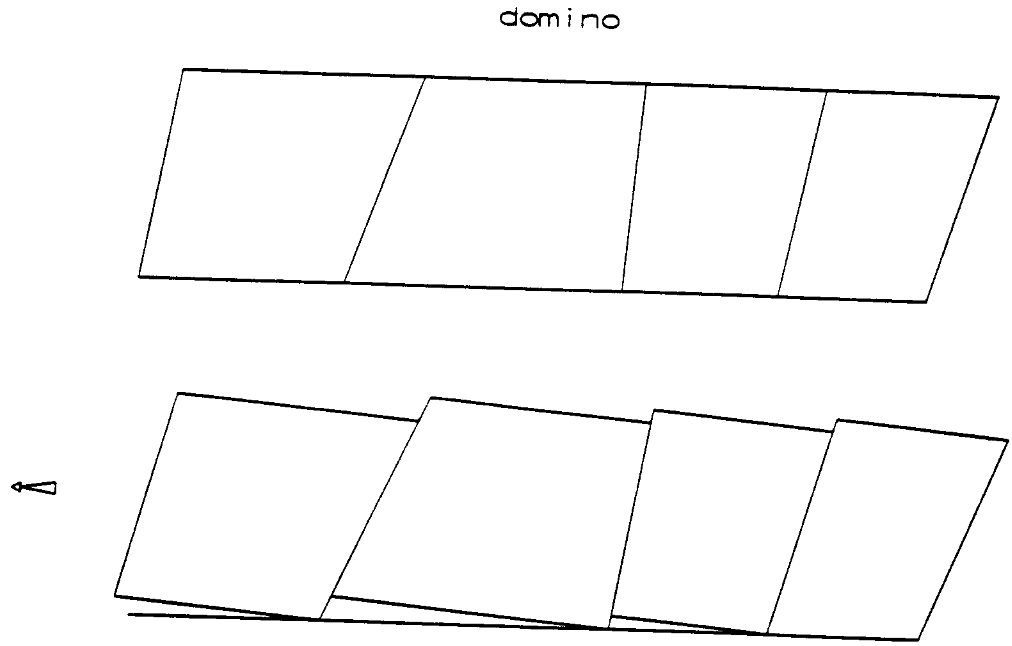


Figure 2-10. Simple domino block model

2.6.2 Applicability of Hybrid Models to Yucca Mountain

Steep normal drag is recorded by Scott and Bonk (1984) on their cross-sections in some of the Yucca Mountain faults, especially the Paintbrush and Solitario Canyon faults. However, although it is possible to construct sections based on this method that represent the large-scale characteristics of Yucca Mountain's structure (Figures 2-14,2-15, 2-16, and 2-17), the same objections (discussed in section 2.5.2) that apply to simple dominoes also apply here.

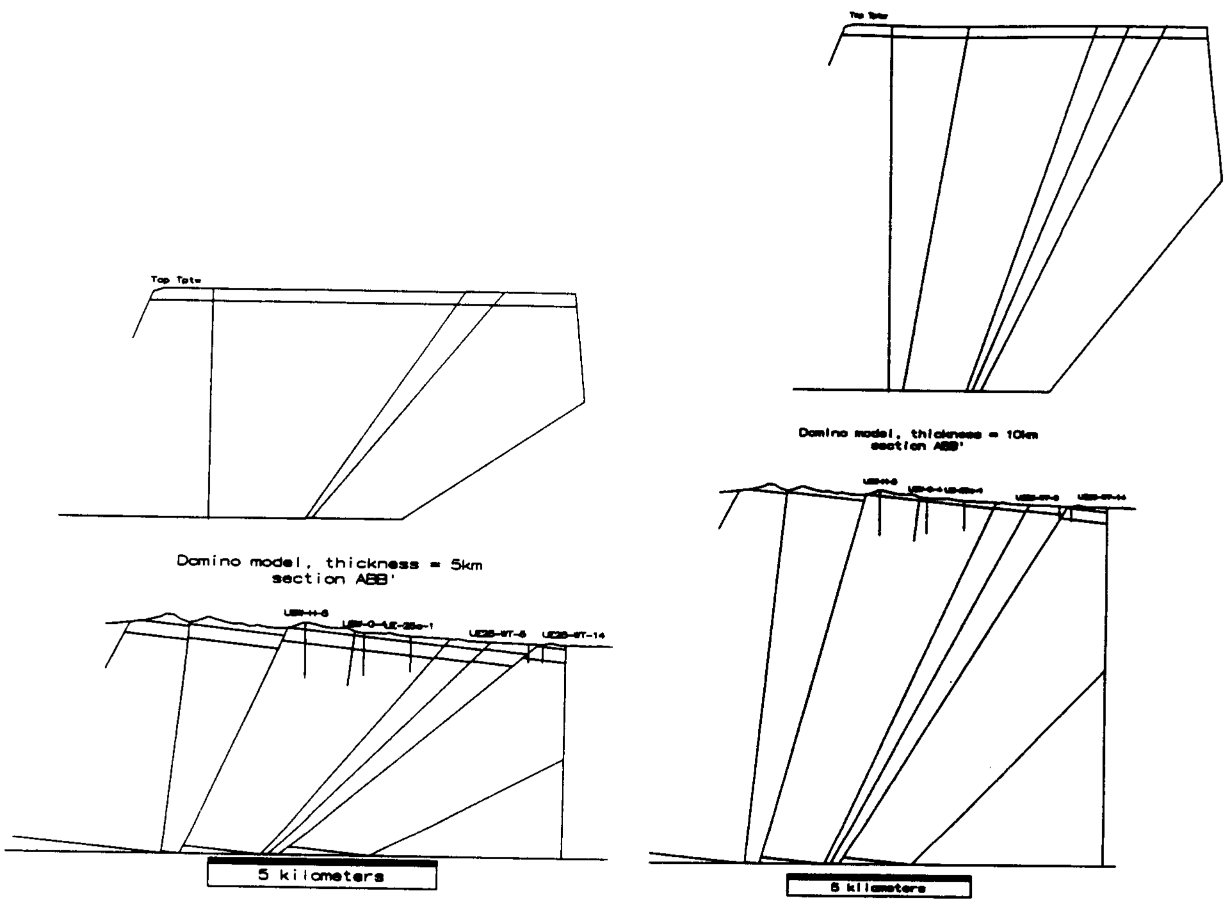


Figure 2-11. Simple domino solutions for Yucca Mountain using the Topopah Springs Member of the Paintbrush Tuff (Tptw) as the marker horizon. Left side shows 5 km depth to initial "detachment" with both restored and deformed states; right side shows restored and deformed states for an initial depth of 10 km. See Young et al. (1991) or Stirewalt et al. (in press) for index map of cross section locations.

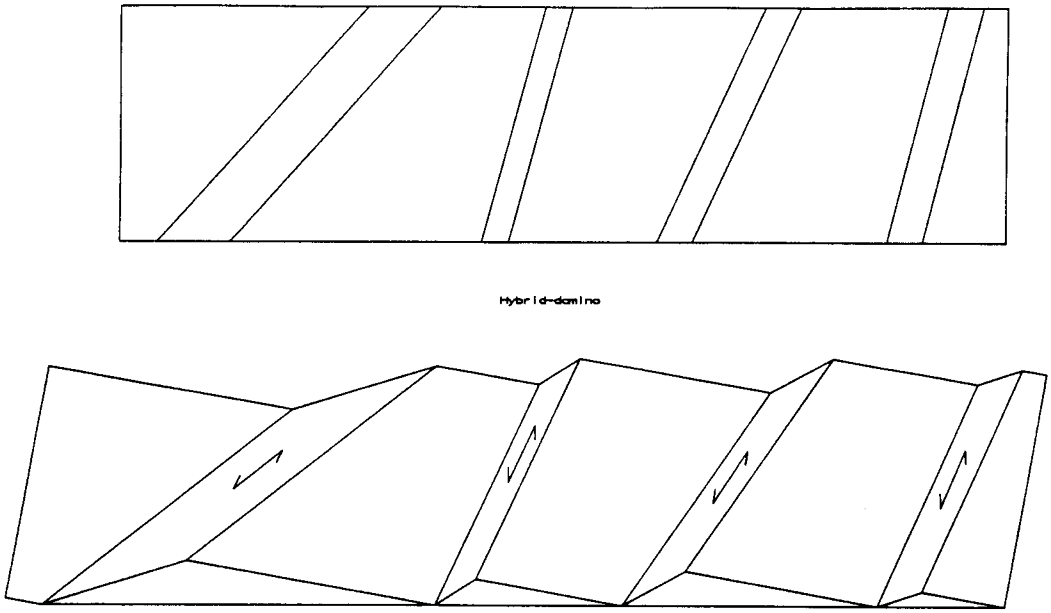


Figure 2-12. A hybrid of the domino model to achieve variable dips at block edges. It is not possible to obtain "rollover" (i.e., dips that are progressively steeper as the fault is approached).

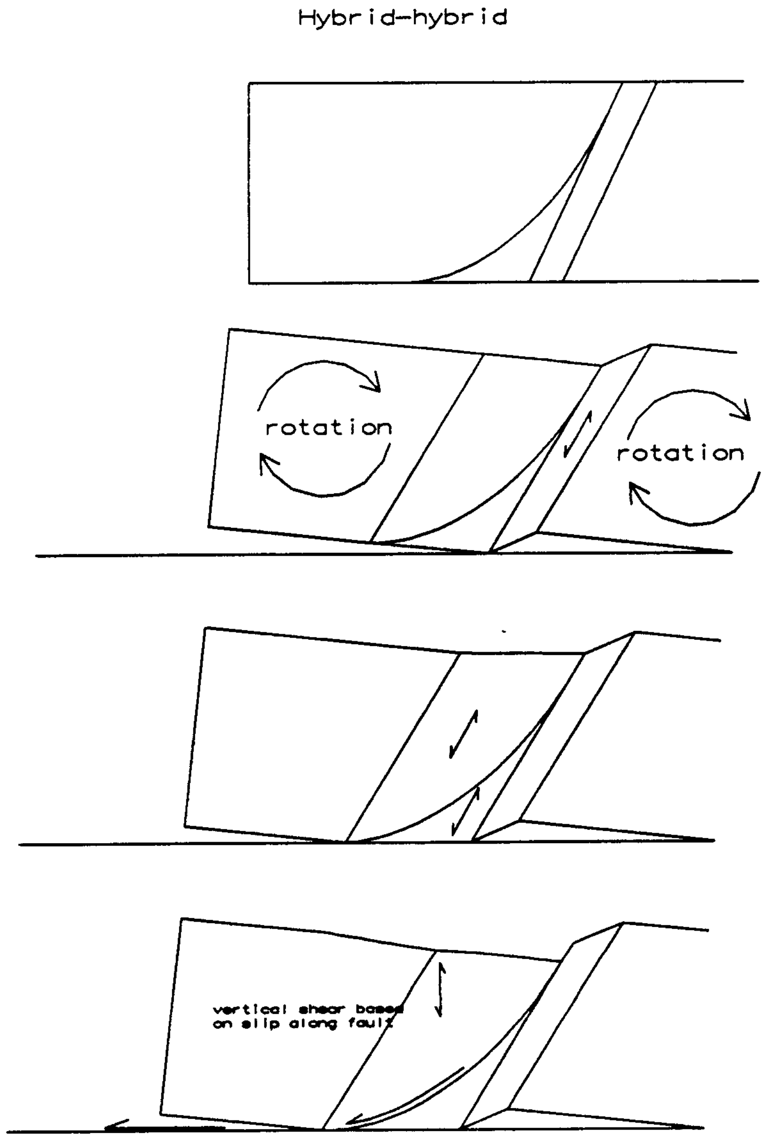


Figure 2-13. A hybrid of the domino model to achieve variable dips at block edges. It is not possible to obtain "rollover" (i.e., dips that are progressively steeper as the fault is approached).

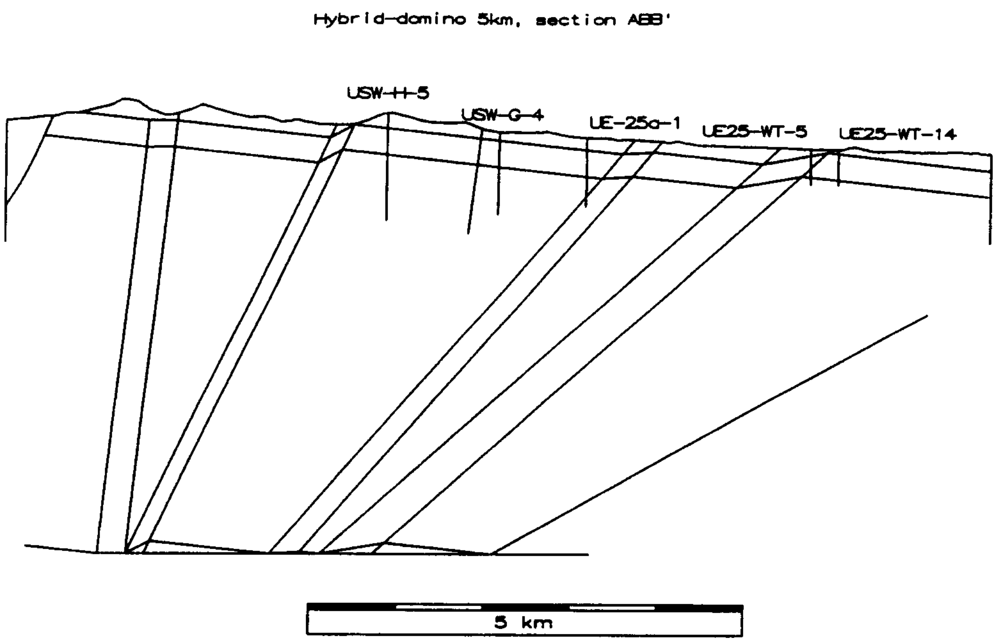


Figure 2-14. An interpretation of Yucca Mountain data using a hybrid domino model and assuming a 5-km depth to base of faulting. There are many similarities with the simple domino model; the principal difference here is the formation of "normal drag" in the fault zones. Section is retrodeformable.

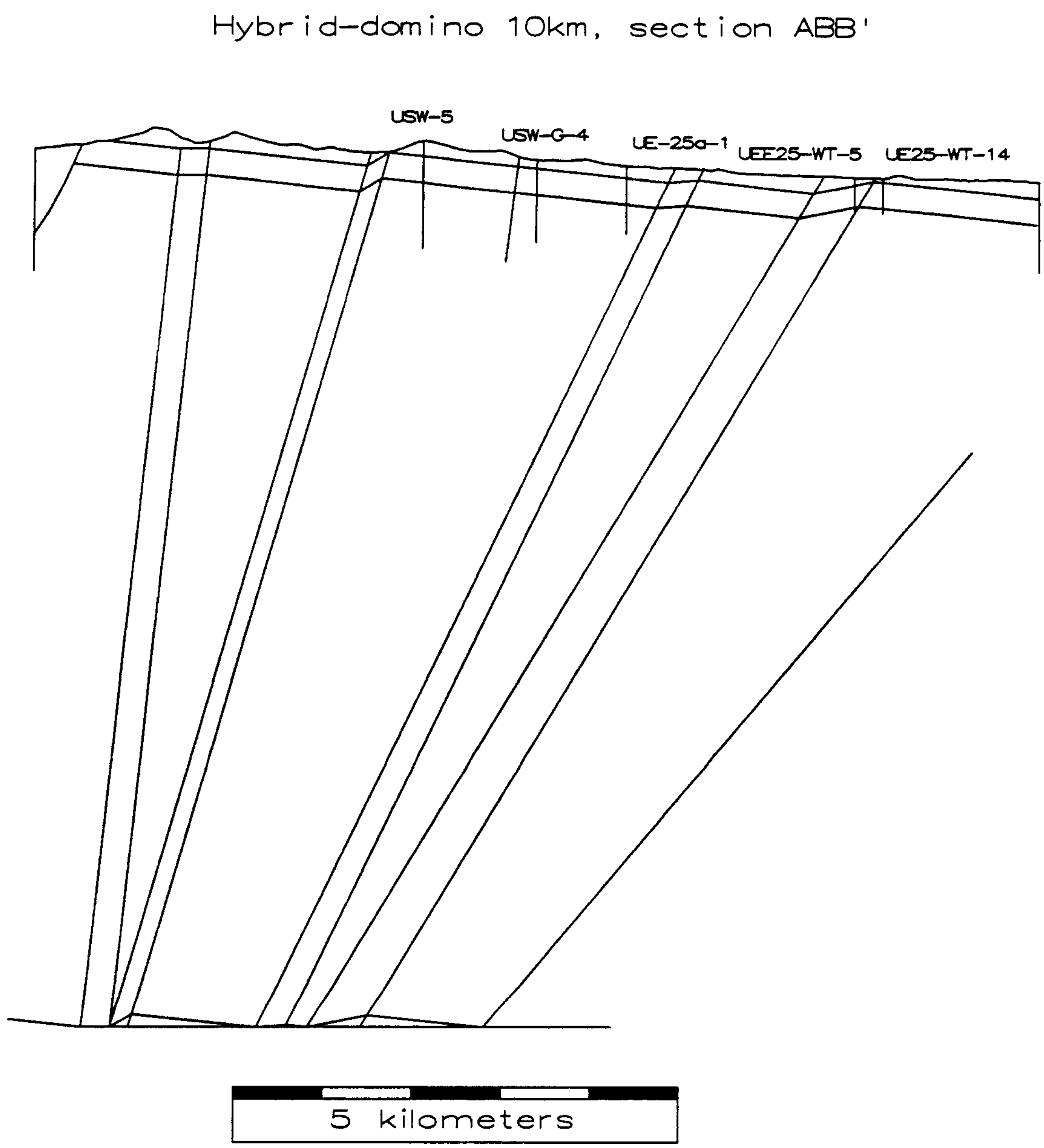


Figure 2-15. An interpretation of Yucca Mountain data using a hybrid domino model and assuming a 10-km depth to base of faulting. There are many similarities with the simple domino model; the principal difference here is the formation of "normal drag" in the fault zones. Section is retrodeformable.

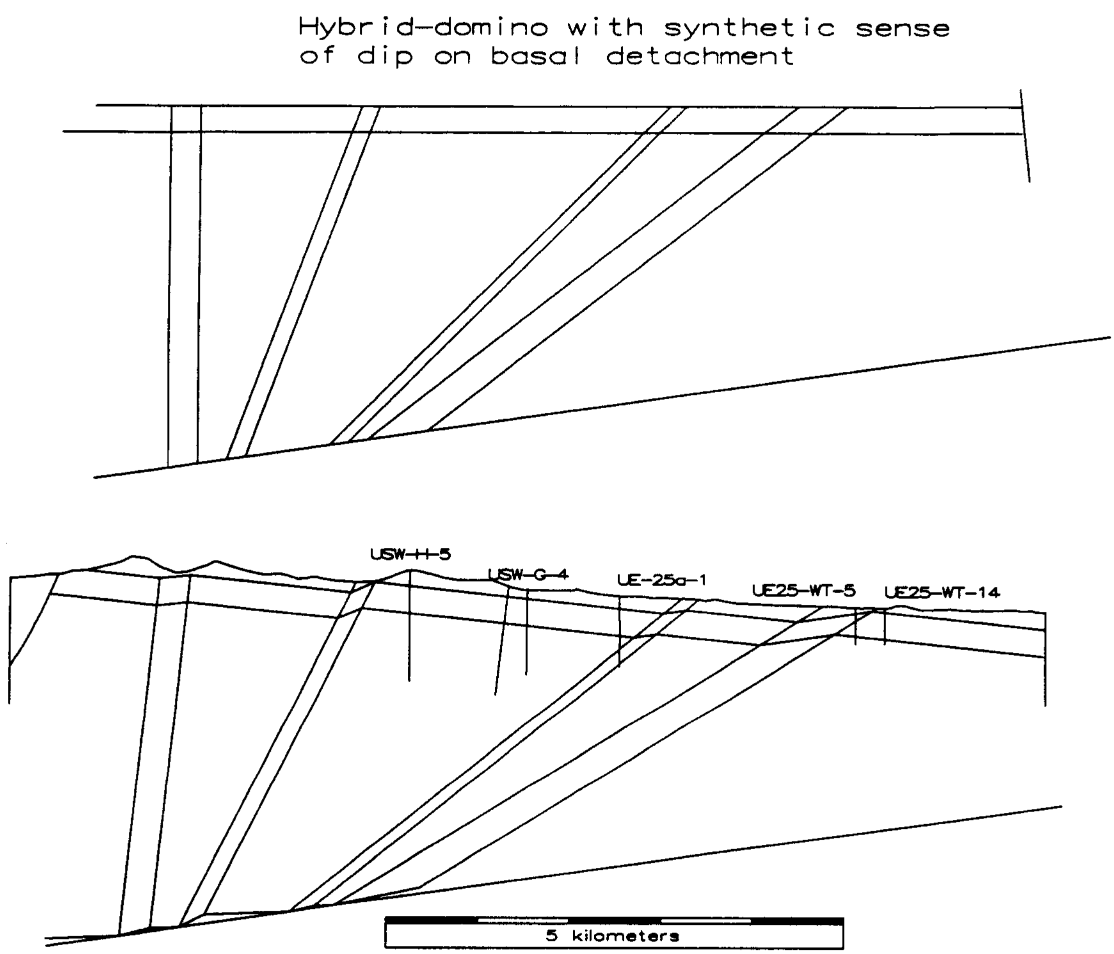


Figure 2-16. Use of a hybrid domino model together with a synthetically dipping detachment. It is not possible to generate "rollover" into the major fault zones.

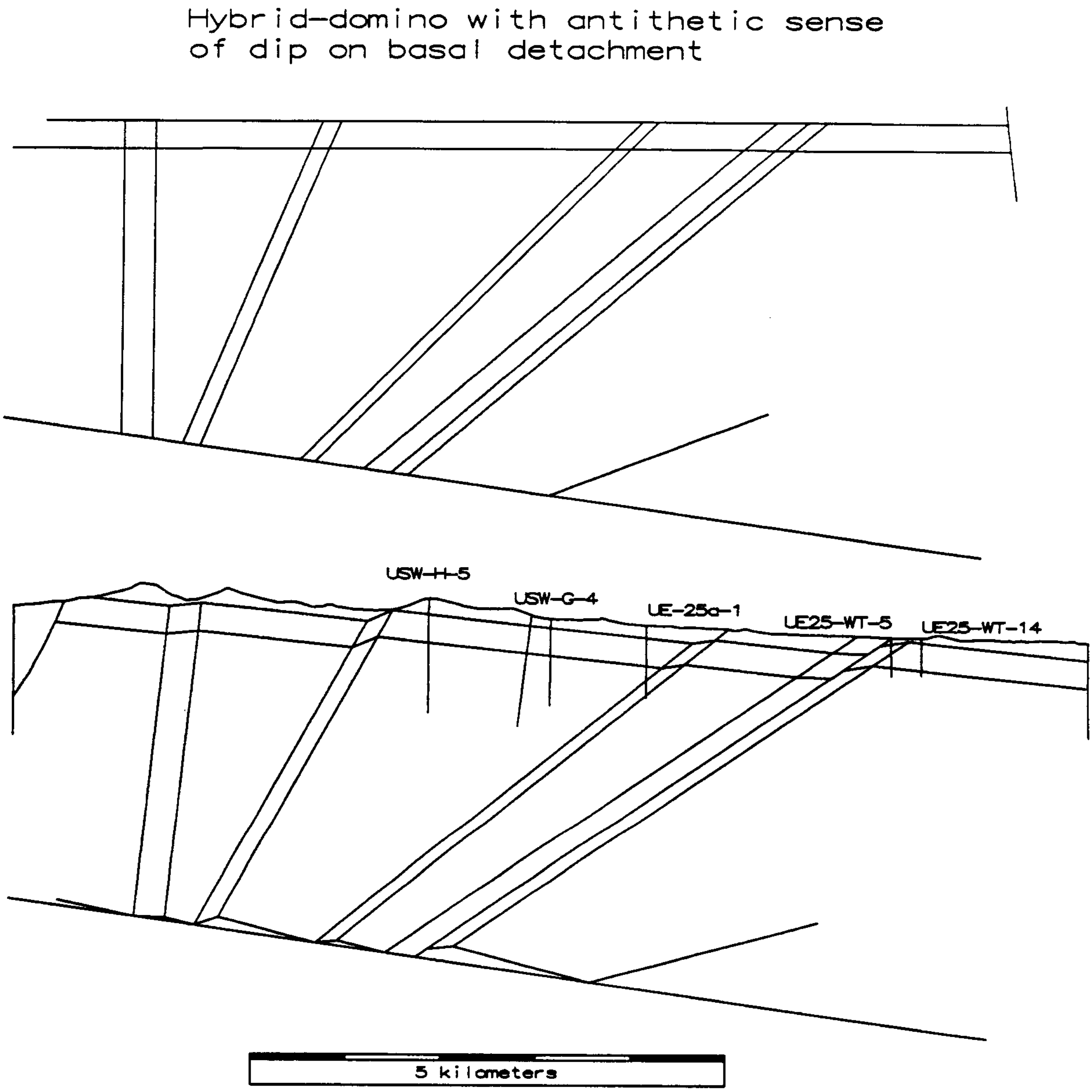


Figure 2-17. Use of a hybrid domino model together with an antithetically dipping detachment. It is not possible to generate "rollover" into the major fault zones.

3 CONTEXT-DRIVEN MODELS

3.1 GROWTH FAULTING

Extensional displacement over listric normal faults most often causes formation of localized hangingwall basins, or troughs somewhat elongated along the strike trend of the bounding fault. Multiple interacting depositional basins may form above faults with complex ramp geometry. Sedimentation that proceeds synchronously with fault motion fills these basins, and tends to result in increased sediment accumulation, or "growth", of the hangingwall stratigraphic sequence, relative to the thickness of correlative units preserved in the footwall (Figure 3-1). Under certain conditions, sedimentation may completely bypass the footwall, while accumulation continues within the hangingwall basin. This process, commonly termed "growth faulting", is well documented in the Gulf of Mexico and many other sedimentary basins (Bally, 1983). In the Yucca Mountain area, synchroneity of fault development and deposition of pyroclastic valley-fill (Maldonado, 1990; Scott, 1990) indicates that growth faulting probably occured. Resultant growth structures may be simply expressed as thickening of certain ash flow tuff units on the down sides of the major normal faults, or more complex areal patterns of flow and cooling units. There is currently insufficient stratigraphic data from the Yucca Mountain area to accurately model hangingwall stratigraphic growth into the interpretations that have been developed, and existing cross-sections assume an essentially "layer-cake" stratigraphy with small variations based on the available shallow well control (Scott and Bonk, 1984; Young et al., 1991; Young et al., 1992).

3.1.1 Effects of Unrecognized Growth on Vertical/Oblique Shear Models

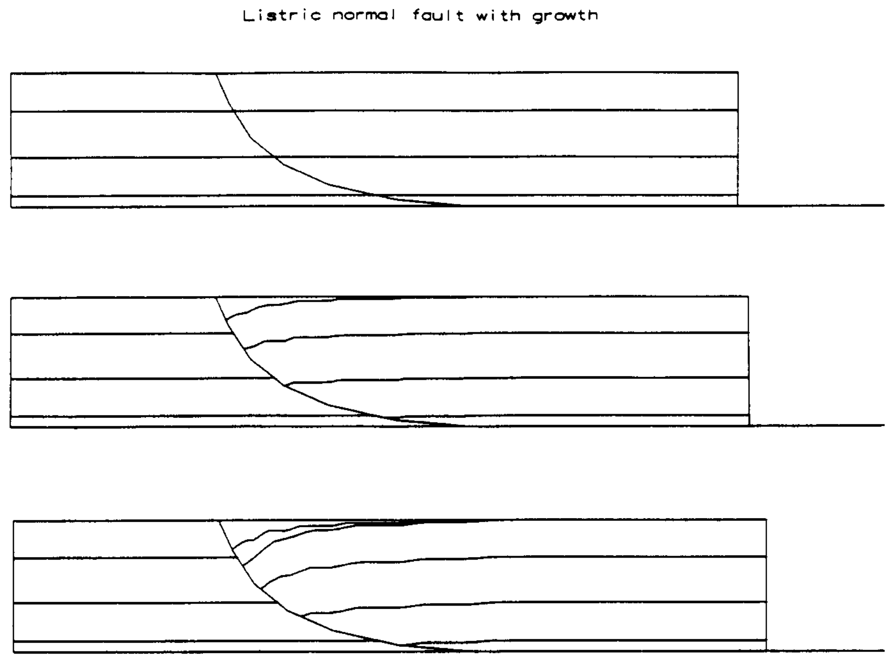
Figure 3-2 shows a listric normal fault system progressively deformed by vertical shear and experiencing sedimentary growth in the rollover region. Using the geometry of the deformed growth horizon(s) and assuming vertical shear, the predicted fault geometry is identical to that which developed the structure. Difficulty arises, however, when trying to locate the footwall cutoff of the growth horizons; in many cases, the growth horizons developed on the hangingwall are not found in the footwall, either because they were not initially developed or because they were eroded. This creates ambiguity in picking an appropriate footwall cutoff level, and hence, can lead to erroneous estimates of fault displacement and predicted fault trajectories.

Figure 3-3 is analogous to Figure 3-2 but is computed for the case of antithetic shear of 70 degrees. The results and conclusions are the same as for vertical shear and also apply to all orientations of oblique shear.

Growth superimposed on vertical or oblique shear systems and unrecognized by the observer will not affect fault shape models that are based on shallow or surface geology provided that good estimates of footwall cutoffs for the key horizons can be made. However, estimates of overall extension, and thus depth to detachment, will be in error by an amount that is related to the total amount of growth that has occurred.

3.1.2 Effects of Unrecognized Growth and Mechanism on Flexural Slip Models

Flexural slip poses a slightly different set of problems. Two possible developmental histories are illustrated in Figure 3-4. The first (on the right) shows the accumulation of sediment on the hangingwall rollover of a developing extensional flexural slip system. In this instance, the growth



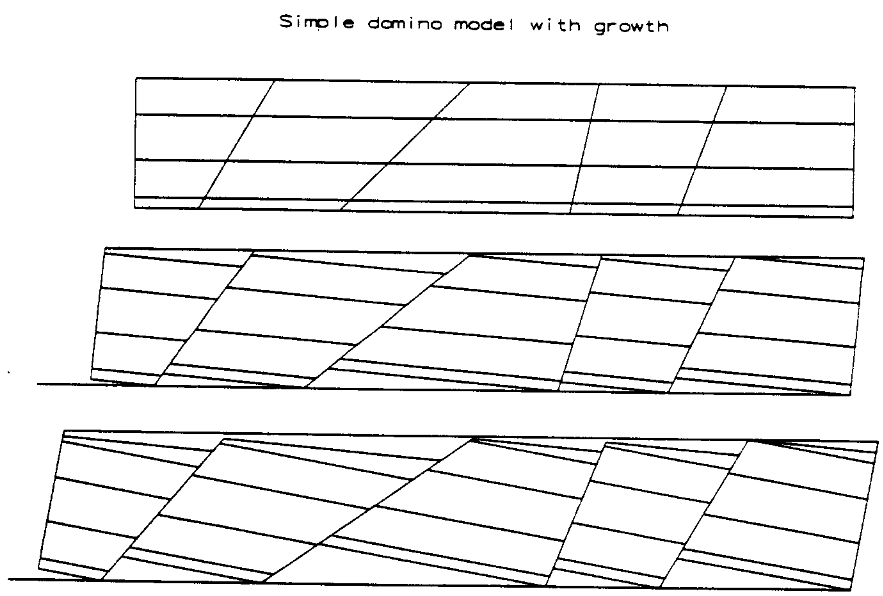


Figure 3-1. Growth superimposed on (upper figure) listric fault model (vertical shear mechanism), and (lower figure) simple domino fault model

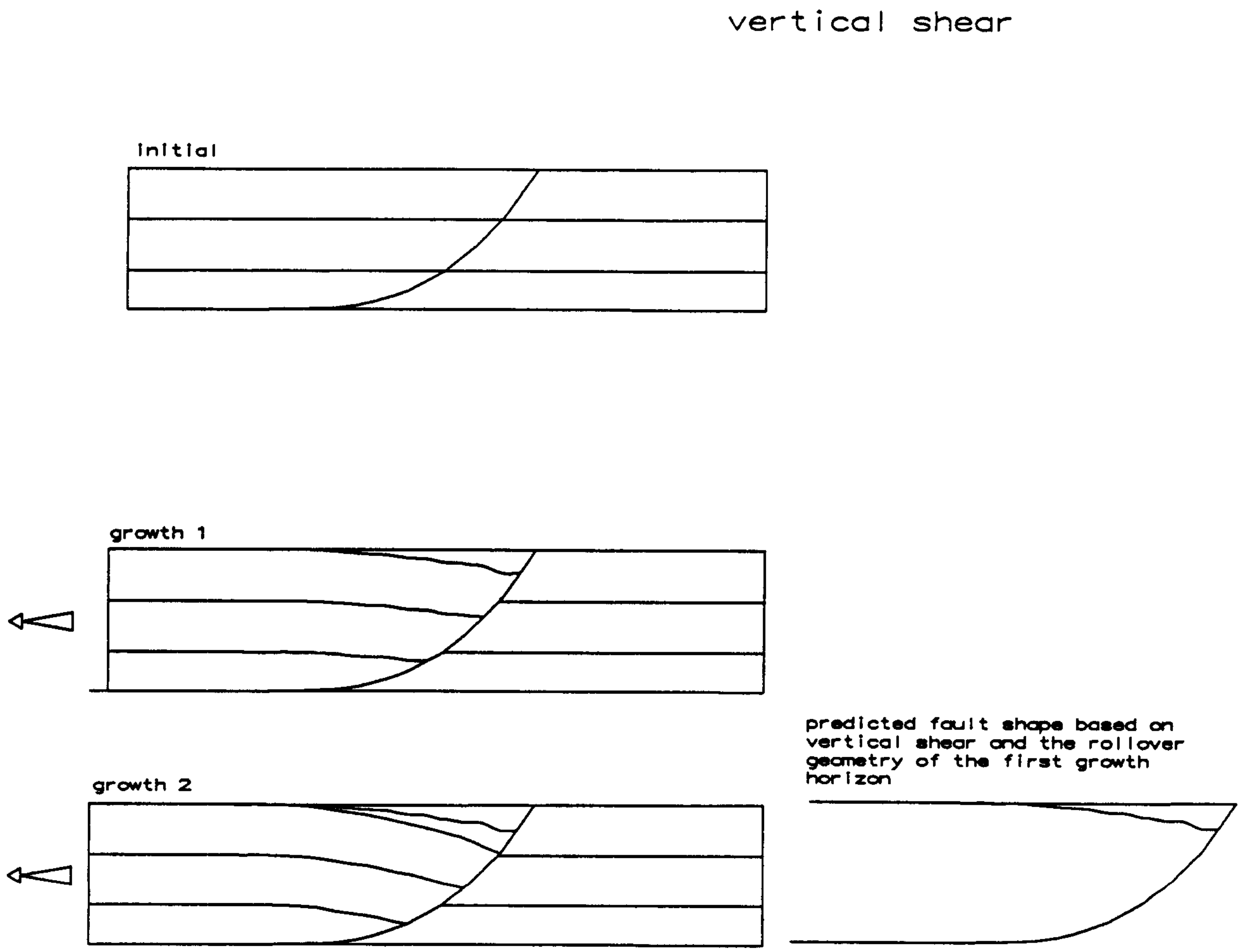


Figure 3-2. Vertical shear mechanism progressively deforming a listric fault system, which is receiving sediment on the hangingwall rollover. Also shown is the predicted form of the fault based on the assumptions that the rollover geometry developed by vertical shear from a horizontal undeformed state which was at the elevation of the highest portion of the hangingwall. The fault geometry is identical to the fault which actually underlies the original structure.

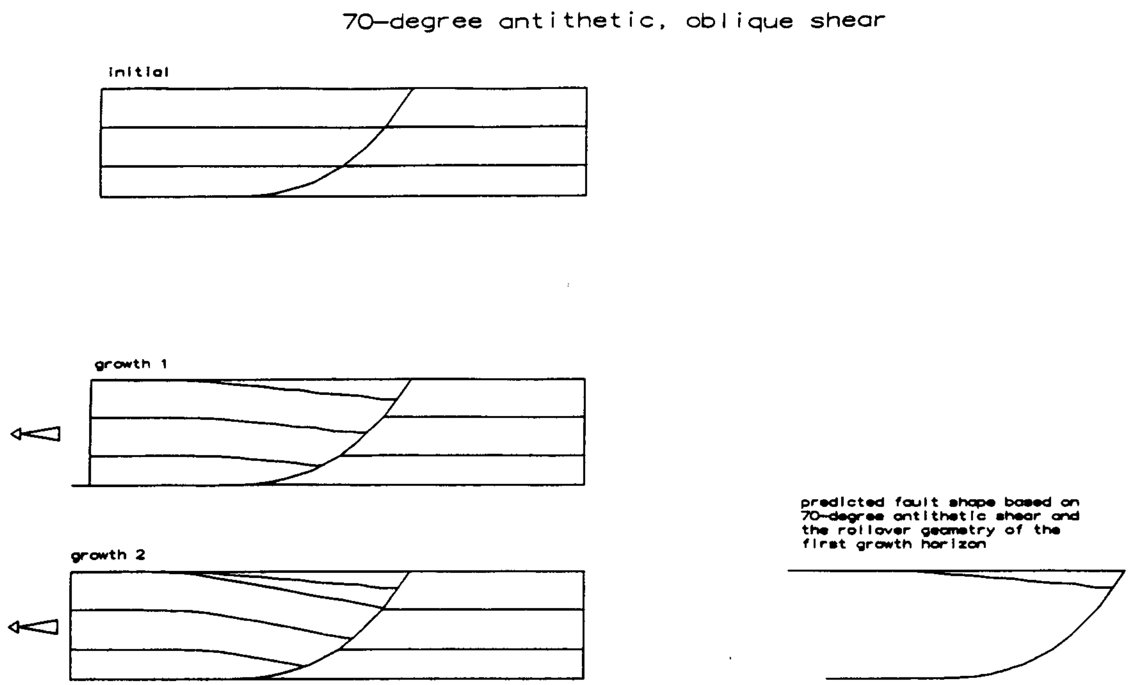


Figure 3-3. 70-degree antithetic oblique shear mechanism progressively deforming a listric fault system, which is receiving sediment on the hangingwall rollover. Also shown is the predicted form of the fault based on the assumptions that the rollover geometry developed by 70-degree oblique shear from a horizontal undeformed state which was at the elevation of the highest portion of the hangingwall. The fault geometry is identical to the fault which actually underlies the original structure.

sediments are being deformed by flexural slip parallel to the bedding of the pregrowth rocks. However, the modeled fault shape is based on the assumption that the flexural slip mechanism is concordant with the growth horizon The premise for this scenario is that the observer has not recognized growth and assumes that the observable rollover geometry contains all the information necessary to construct the fault shape.

Secondly (on the left), a growth sequence that is not well layered, or is less indurated may have deformed by some generalized simple shear mechanism (here assumed to be vertical shear), geometrically discordant from the underlying pregrowth section. A fault trajectory modeled by assuming that the growth rollover geometry contains all the necessary information to construct the fault, and that the entire hangingwall system deformed by vertical shear, is significantly different from the actual fault responsible for the structure.

In the case of unrecognized growth, perhaps accompanied by a change in deformation mechanism, superimposed on a flexural slip system, unless the full growth history can be obtained (e.g., from seismic reflection studies or drilling) serious errors will be made in the prediction of fault trajectories from shallow or surface geological data.

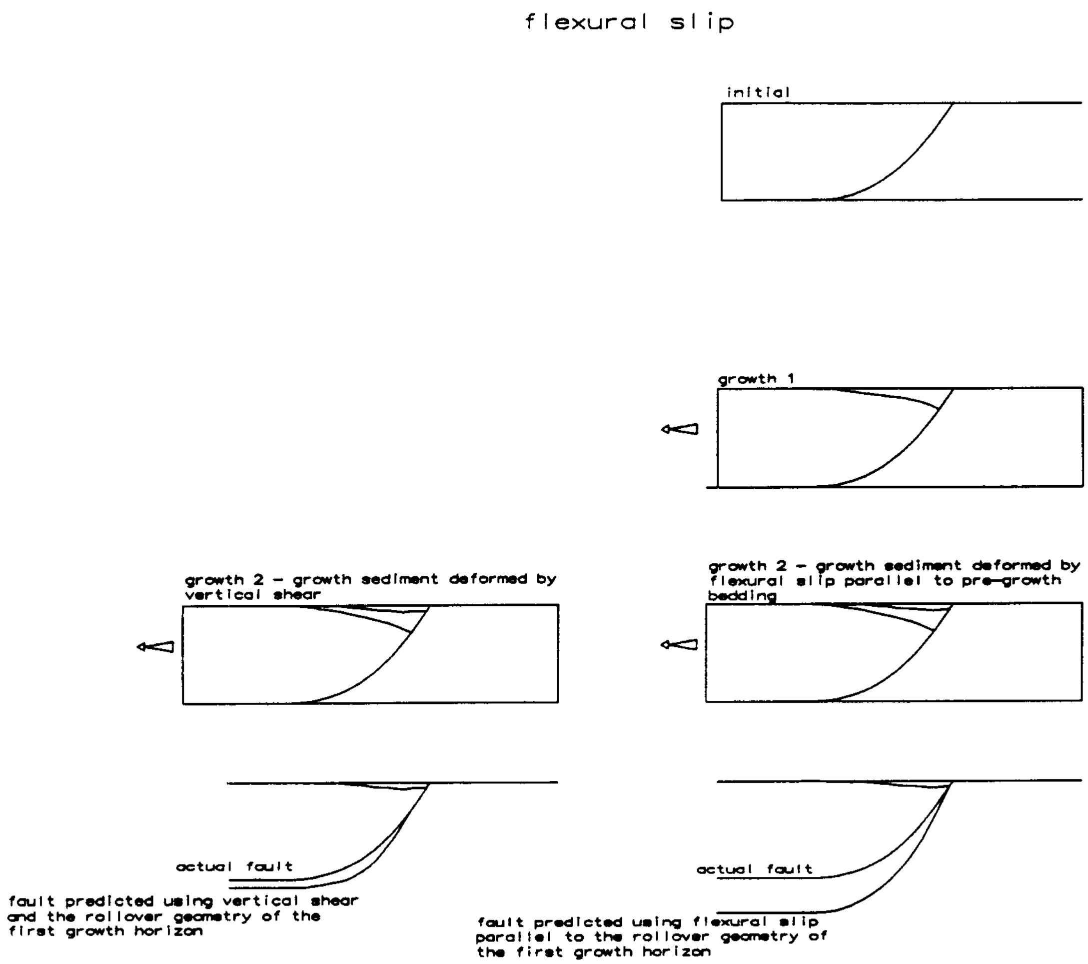


Figure 3-4. Extensional flexural slip system with growth. See text for explanation.

3.1.3 Effects of Unrecognized Growth on Slip-Line Models

Figure 3-5 shows a listric normal fault system progressively deformed by slip-line deformation and experiencing sedimentary growth in the rollover region. Using the geometry of the deformed growth horizon(s) and assuming slip-line deformation, the predicted fault geometry is identical to that which developed the structure. As in the case of vertical or oblique shear, however, difficulty arises when trying to locate the footwall cutoff of the growth horizons; in many cases, the growth horizons developed on the hangingwall are not found in the footwall, either because they were not initially developed or because they were eroded; this creates ambiguity in picking an appropriate footwall cutoff level, and hence, can lead to erroneous estimates of fault displacement and predicted fault trajectories.

Growth superimposed on a slip-line system and unrecognized by the observer will not affect fault shape predictions that are based on shallow or surface geology provided that good estimates of footwall cutoffs for the key horizons can be made. However, estimates of overall extension will be in error by an amount that is related to the total amount of growth that has occurred.

3.1.4 Effects of Unrecognized Growth on Domino Models

Figure 3-6 shows the effects of growth superimposed on a simple domino block system. Block rotation is also assumed for the growth sediments in this case. Growth horizons will have lower dips than the pregrowth rocks; thus, restoration based on these dips will underestimate the total rotation and, thus, underestimate the overall shortening. Fault orientations can, however, be constructed accurately.

3.1.5 Compaction of Growth Sediments

None of the foregoing discussion of faulting-related stratigraphic growth has considered the effects of compaction on the development and interpretation of hangingwall structures. Burial compaction of growth faulted sedimentary rocks is known to have significant influence on actual listric fault systems and is demonstrated to be important in simple shear fault models (Xiao and Suppe, 1989). It is well established that sediments accumulating in a growth setting experience compaction as a function of their loss of pore space with increasing burial depth (Sclater and Christie, 1980; Baldwin and Butler, 1985). The behavior of pyroclastic material in a similar setting is not documented; however, it is probable that accumulations of tephra supported by vapor or liquid phase fluid vesicles, indicated by preservation of pumice and lithophysae, experience compaction in an analogous manner; by ductile compression, and subsequent welding, of discrete cooling units. Temperatures within ash flow sheets remain high enough to allow ductile deformation of individual glass shards. Porosity occlusion, or compaction, of the interior of the sheet occurs relatively early in the cooling history of the flow. Subsequent mechanical (burial) compaction of the high porosity, "quenched" contacts of the flow is probably not significant. Figure 3-7 illustrates the effects of ignoring compaction when predicting fault trajectories using vertical shear. In all cases, the fault displacement will be overestimated by some amount dependent on the degree of compaction. Sufficient data are not currently available to effectively assess the influence of compaction and welding on models of faulting, and this issue is not addressed here. However, since the ash flow tuff units constitute most of the observable hangingwall stratigraphy at Yucca Mountain, overall influence on fault shape may be significant. This is an important area of consideration for future work on models of faulting at Yucca Mountain.

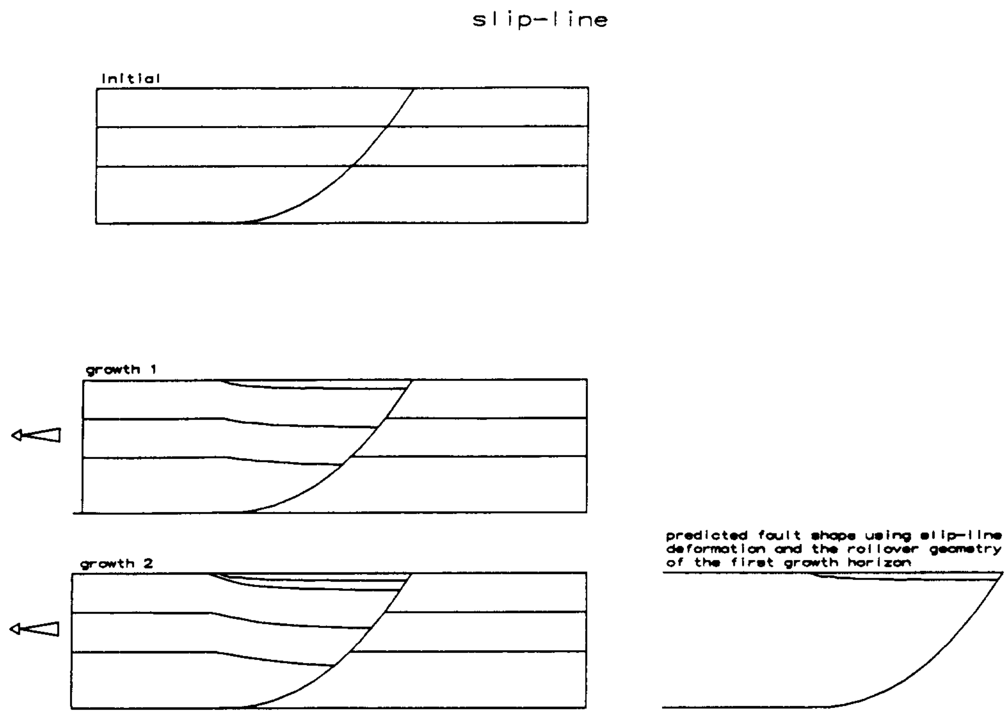


Figure 3-5. Extensional listric fault system deformed by slip-line deformation and accumulating sediment on the hangingwall rollover. In the bottom right of the figure is the fault constructed from the rollover geometry based on the assumption that the hangingwall deformed by slip-line deformation; the fault is identical to that on which the structure developed.

3.1.6 Significance of Growth for Yucca Mountain

It is very likely that the faults at Yucca Mountain were active during accumulation of tephra (Maldonado, 1990). The net effect of this, regardless of actual or assumed deformation mechanism, is that the overall estimate of extension based on shallow wells and surface geology is probably an underestimate.

3.2 DETACHED COVER MODELS

Jackson et al. (1988) discuss briefly the concept of a sedimentary carapace deforming along listric fault systems that are detached from its rigid domino block substrate (see Figure 1-2). This style of deformation has long been recognized in petroleum exploration of passive continental margins (e.g., Bally, 1983; Figure 1-2). Beneath the Yucca Mountain area, a major unconformity exists between Paleozoic rocks and the Tertiary pyroclastic sequence. The lower Paleozoic rocks consist of completely lithified, even metamorphosed, carbonates and clastics that might reasonably be expected to behave in a rigid fashion to depths of 8 to 10 km. The stratigraphic succession of Tertiary pyroclastic accumulations

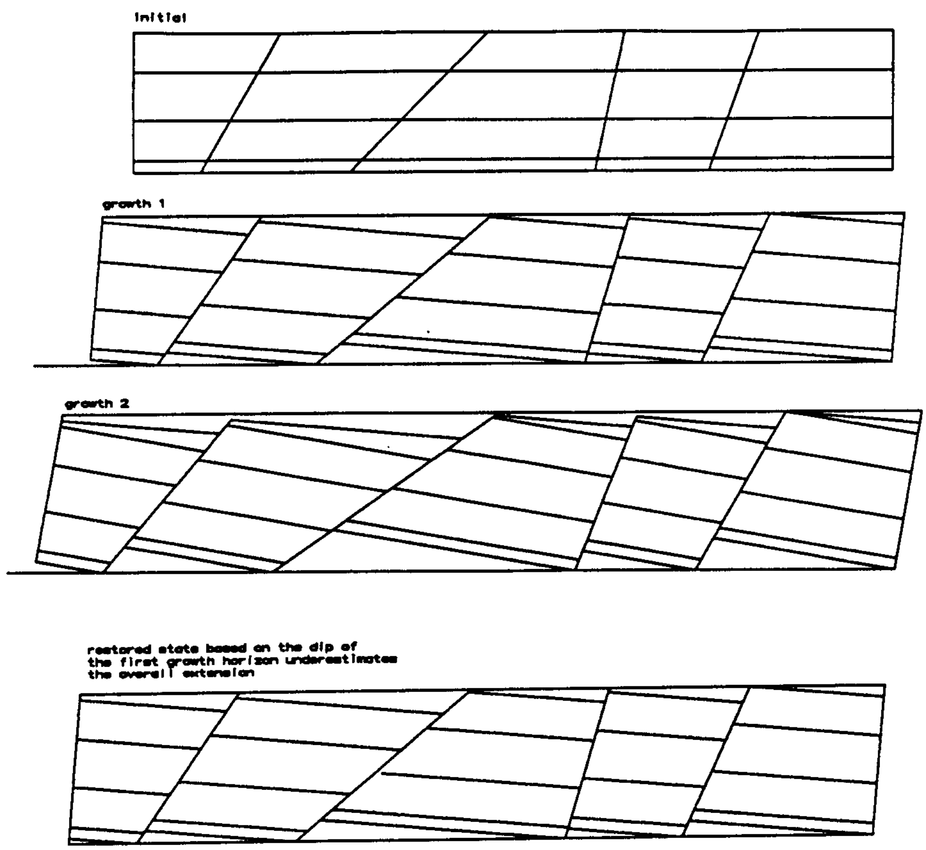


Figure 3-6. Domino block system with superimposed sedimentary growth. Growth sediments are assumed to have deformed by block rotation. See text for explanation.

may have had sufficiently different material properties during extensional faulting to permit them to deform by a different mechanism. Indeed, it has been assumed (Maldonado, 1990) that the Paleozoic/Tertiary unconformity has acted as a major detachment surface.

Figure 3-8 shows a possible interpretation of Yucca Mountain using this model. The section was constructed using 70-degree antithetic shear as a deformation mechanism for the pyroclastic cover (listric fault region) and domino block deformation for the Paleozoic basement. In order to construct listric faults soling at the level shown (approximately 3 km depth) it is necessary to assume a predeformational elevation of the top of the Topopah Springs Member of the Paintbrush Tuff at approximately 1525 m—the lowest permissible by available surface geological data; this, coupled with the antithetic shear deformation, produces a shallow detachment. The domino-deformed basement is purely schematic, there is no data to support this interpretation, and there are no constraints on the geometry of the sub-cover

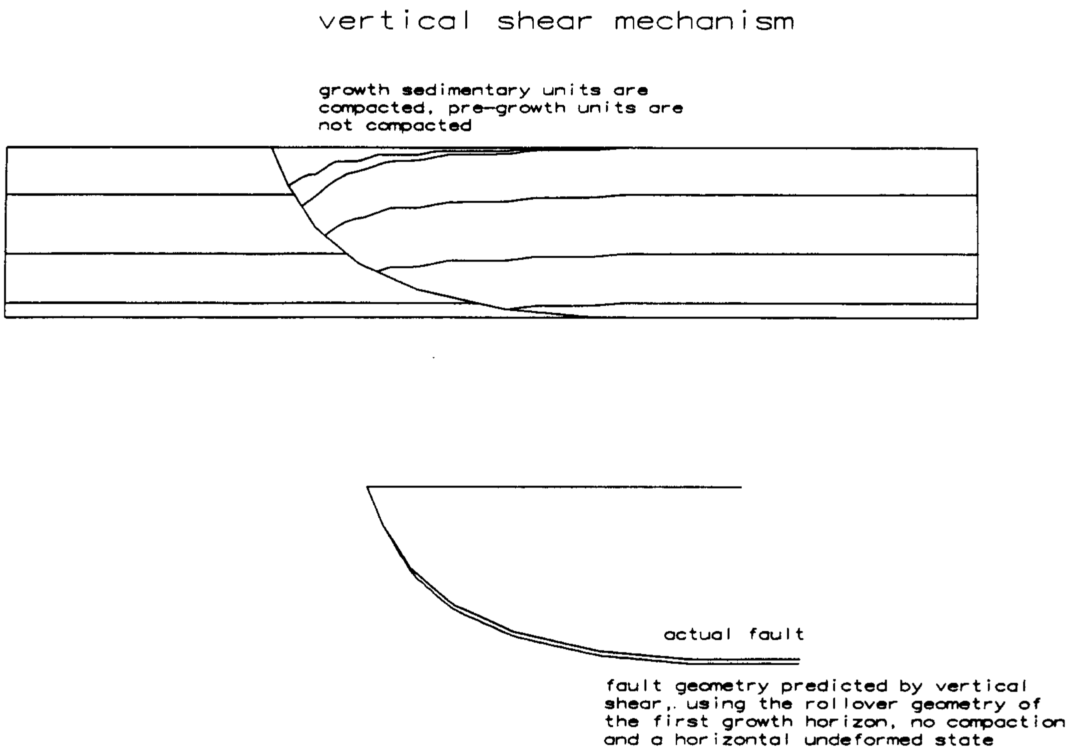


Figure 3-7. Effects of ignoring compaction when predicting fault trajectories using vertical shear

faults. The lack of data on the stratigraphic thicknesses of the Tertiary pyroclastic sequence is a severe limitation on this style of interpretation. Currently available information and a simple "layercake" approach indicates that the top of the Paleozoic may exist at depths of 1500 to 2000 m; this is shallower than implied by the interpretation shown in Figure 3-8.

Even though Maldonado (1990) refers to the Bullfrog Hills detachment as separating the Tertiary from Paleozoic rocks in that area, his paleotectonic reconstruction clearly shows that the development of the listric fault system that accommodated the large extensions in that area must have extended much deeper into the sub-Tertiary sequence (Maldonado, 1990; his figure 10). In addition, recent interpretations of the southern Basin and Range as being composed of many displaced fragments of the remnant Mesozoic orogen (Wernicke et al., 1988) also require that the major extensional fault systems be rooted well below the level of the base-Tertiary unconformity. None of this negates the possibility of detached cover extension, but it removes the "necessity" of utilizing the unconformity as a detachment surface.

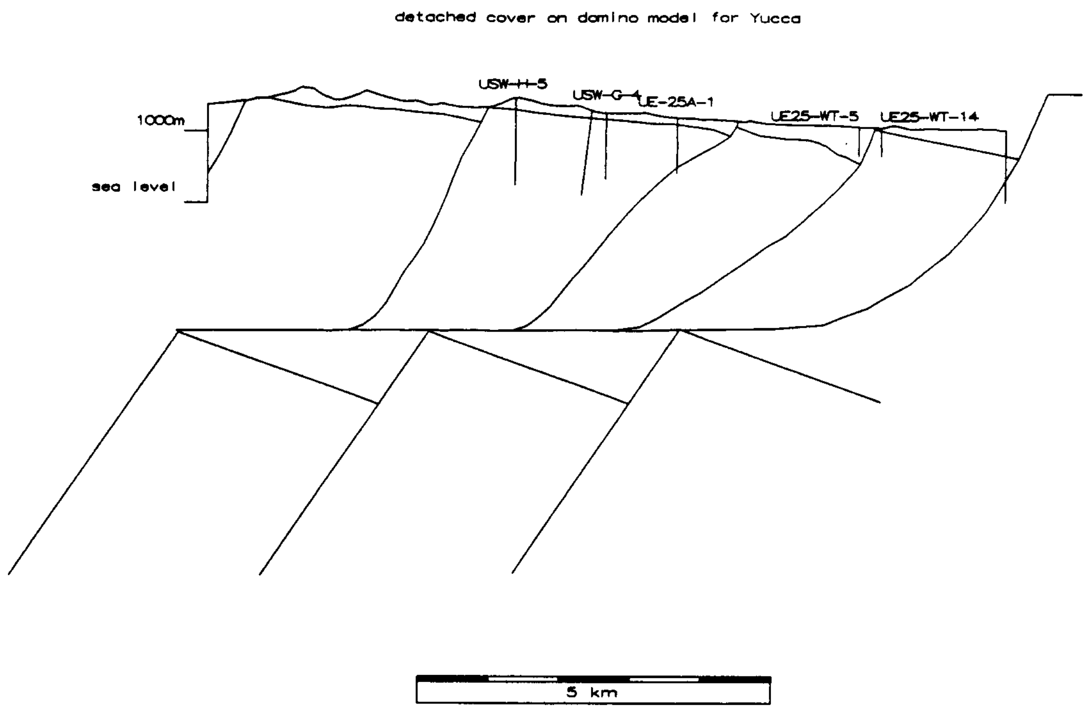


Figure 3-8. Detached cover interpretation of Yucca Mountain. The index horizon is the top of the Topopah Spring Member of the Paintbrush Tuff. The Tertiary pyroclastic sequence is assumed to have deformed by 70-degree antithetic shear from an undeformed horizontal "regional" at an elevation of 1525 m. For discussion, see text.

It is likely that the nature of the contact between Tertiary volcanic rocks and underlying Paleozoic and Proterozoic rocks is dependent on structural position. The contact is a detachment fault in the Bullfrog Hills area where Tertiary volcanic rocks dip steeply into the contact. At Yucca Mountain, there is no indication that the volcanic section is substantially discordant at the unconformity.

Finally, the rollover geometries developed at Yucca Mountain are consistent with listric faults that sole at depths that are deeper than the base-Tertiary unconformity for any realistic oblique shear angle (Young et al., 1991; Stirewalt et al. In press); therefore, the detached cover model is not likely to produce good and reasonable interpretations.

Until better information about the sub-surface geometries of faults and/or the depth of the base-Tertiary unconformity under Yucca Mountain is available, detached cover models should be considered as speculative and unsupported by data.

3.3 THE ROLE OF ISOSTASY

Extreme extension accommodated by listric or low-angle normal faults attenuates at least the upper crust and results in concomitant tectonic denudation of the fault surface. If a significant thickness of hangingwall rocks is removed from above the footwall, isostatic rebound will result (Spencer, 1984; Lister and Davis, 1989). Figure 3-9 shows in simplified form how this can occur.

The wavelength of the Bare Mountain/Yucca Mountain antiform/synform pair is comparable to that modelled by Spencer (1984). Interpretations of Yucca Mountain as a little-extended portion of an extended hangingwall (Lister and Davis, 1989), and the Bare Mountain fault as an isostatic rebound accommodation fault are considered to be feasible (Scott, 1990; Figure 3-10).

3.4 EXPLOITATION OF PRE-EXISTING CONTRACTIONAL STRUCTURES

Where extension is superimposed on a compressional orogen, it is possible that extensional faults will sole into thrusts at depth (Gibbs, 1984). Thrust faults commonly have listric geometry, and they may act as mechanical discontinuities, or preweakened zones that are exploited during the extensional phase. In particular, thrust fault ramps (the portion of the fault that cross-cuts bedding) may be locally significant stress risers; thus localizing later ramps of extensional systems.

The Paleozoic rocks that underlie Yucca Mountain, and predate the accumulation of Tertiary volcanics, were involved in the mid-Paleozoic Antler and Mesozoic Sevier orogenies (Wernicke et al., 1988). Thrust faults and folding exist within these orogens, although the precise geometrical form of these structures beneath Yucca Mountain is not known. It is possible that Antler and Sevier age structures have influenced the later extensional features, although to what extent is not at present decipherable.

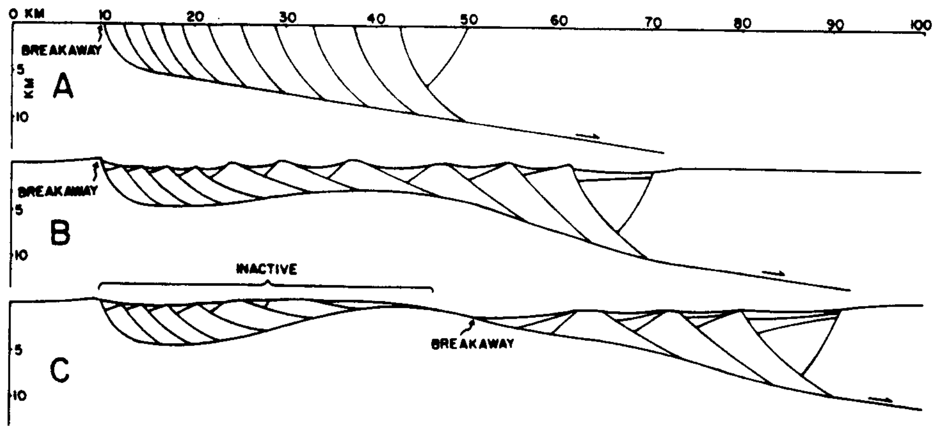
3.5 MULTIPLE GENERATIONS OF FAULTING

Continuing extension of continental crust creates multiple generations of faults. As early-formed faults rotate into progressively less favorable orientations for accommodating extension or become uplifted by isostatic rebound (Proffett 1977; Jackson and McKenzie, 1983; Gibbs, 1984; McClay and Ellis, 1987; Lister and Davis, 1989), steeper, faults evolve and deactivate the earlier systems.

Applying this concept to Yucca Mountain permits the interpretation of the Bare Mountain fault as one of these later, steeply-dipping faults that has cross-cut or disrupted, the listric system underlying Yucca Mountain itself (Scott, 1990). In addition, the Fortymile Wash fault (Young et al., 1992) may be related to this fault or may have been reactivated as an antithetic fault.

3.6 MULTIPLE DETACHMENTS

Contractional fault systems frequently operate along more than one detachment level simultaneously. The same may be true for extensional terrains (Gibbs, 1984; McClay and Ellis, 1987). Interaction between two or more detachments leads to the development of a variety of complex structures such as hangingwall synclines, crestal collapse grabens, and extensional duplexes.



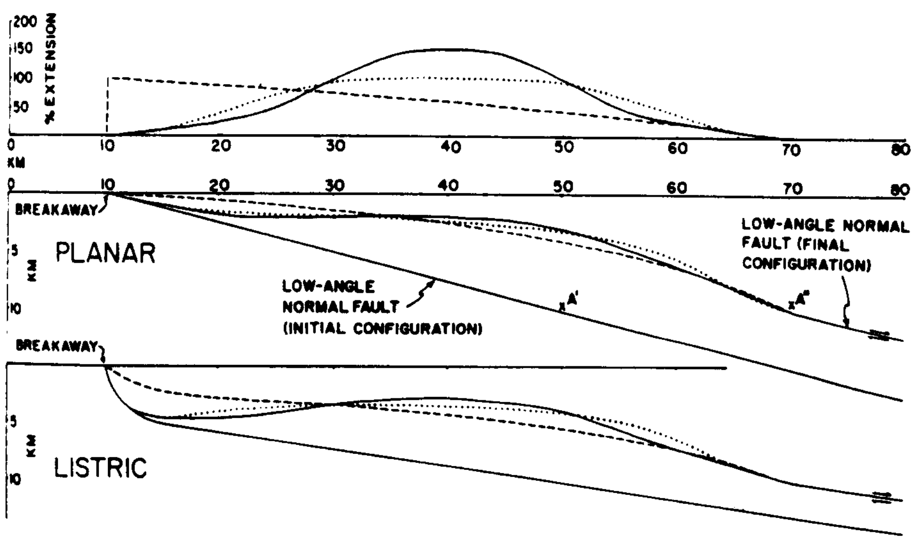


Figure 3-9. Figures 1 and 2 from Spencer (1984) showing the effects of tectonic denudation and the formation of footwall uplift by isostatic rebound

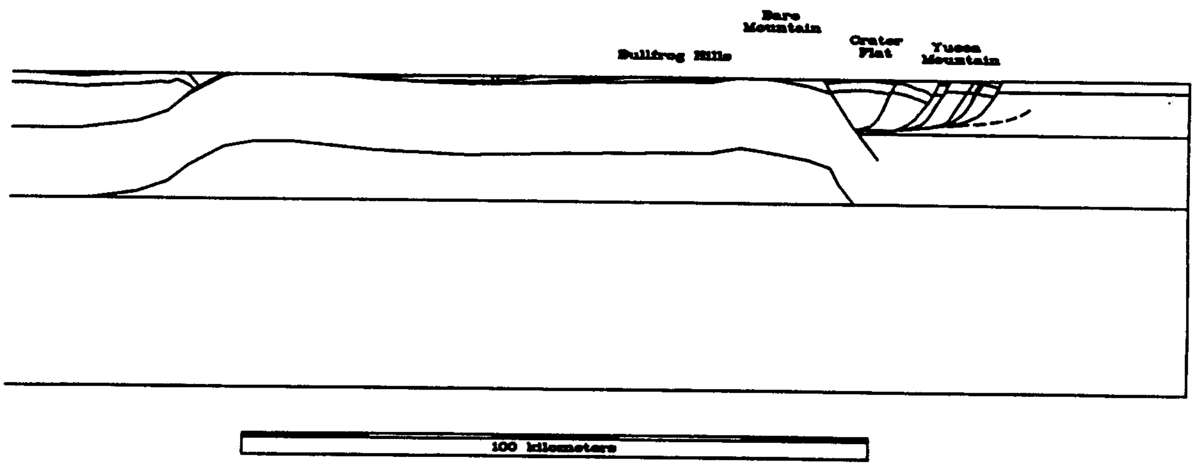


Figure 3-10. Conceptual regional setting of Yucca Mountain. Sources for section are Maldonado (1990), Scott and Bonk (1984), Spencer (1984), and Lister and Davis (1989). Cross section is forward-modeled to deformed start, and is therefore balanced and retrodeformable.

A preliminary interpretation of seismic line AV-1 (about 30 KM southeast of Yucca Mountain) utilizes a multiple detachment model to explain features at the west end of the line (Morris et al., 1992; and Figure 3-11). There is currently no direct evidence to support such a model at Yucca Mountain.

3.7 THREE-DIMENSIONAL CONSIDERATIONS

3.7.1 Pull-Apart Tectonic Setting

Yucca Mountain is located on the eastern margin of Walker Lane, a crustal-scale tectonic zone that marks a transition from mostly north-south Basin-Range physiography on the north, to the more northwest-southeast physiographic trends of Death Valley and the Mojave Desert. The region is one of crustal pull-apart extension bounded by transform zones of strike-slip (Wernicke et al., 1988). Numerous microcosms of this geometry exist within the belt, for example, the Panamint Valley (Burchfiel et al., 1987).

Yucca Mountain and its surrounding area may also be of this nature (Figures 3-12 and 3-13). The dextral shear couple imposed by the strike-slip zones south of Yucca Mountain would create extension along a WNW-ESE axis, roughly perpendicular to the surface traces of the major normal faults at Yucca Mountain. Scott's (1990) analysis of fault orientations and paleostresses based on slickenside

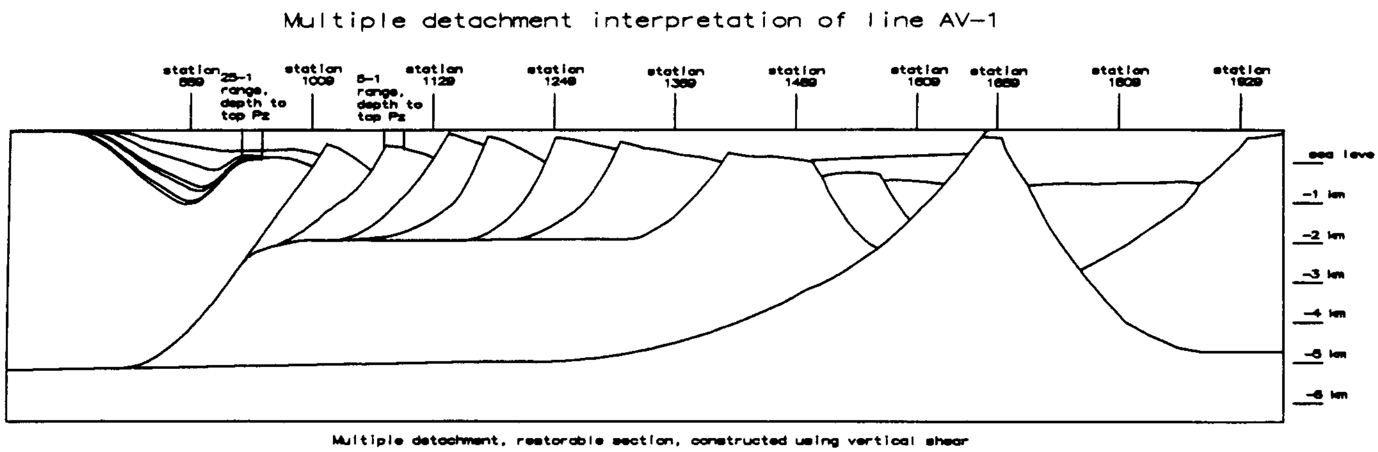


Figure 3-11. Multiple detachment interpretation of AV-1 seismic reflection line (Morris et al, 1992) using vertical shear. Cross section model is retrodeformable.

striations is perfectly compatible with this geometry; the toggling of sigma-1 and sigma-2 between vertical and horizontal (NNW-SSE) is a function of interactions between fault blocks and generates normal motion or strike-slip motion, respectively. Normal displacement on appropriately oriented faults can continue if the margins of the shear zone propagate into the undeformed crust bordering it. Such a history of shear zone growth would imply that total deformation decreases from the older parts of the zone towards its margins (Ramsay, 1967), with a concomitant decrease in rotation of deformed blocks. Scott (1990) documents a 30-degree differential in (clockwise) rotation from south of Yucca Mountain to the northern limit of Yucca Mountain, in conjunction with a difference of 60-percent extension south of Yucca Mountain to 10 percent at the northern end. The rotation implies a net shear strain south of Yucca Mountain of approximately 0.65, while the extension yields a shear strain of 1. The discrepancy may be accounted for by the partial decoupling of the extensional faults from the shear system once the normal faults have formed; for strain compatibility reasons the normal fault system will tend to be resistant to rotation but will continue to accommodate extension (Figure 3-13).

Pull-apart deformation at Yucca Mountain is the most likely model for the range-scale tectonic setting, and construction of cross-sections south of the mountain represent an important next step in characterizing the three-dimensional structural setting of the area.

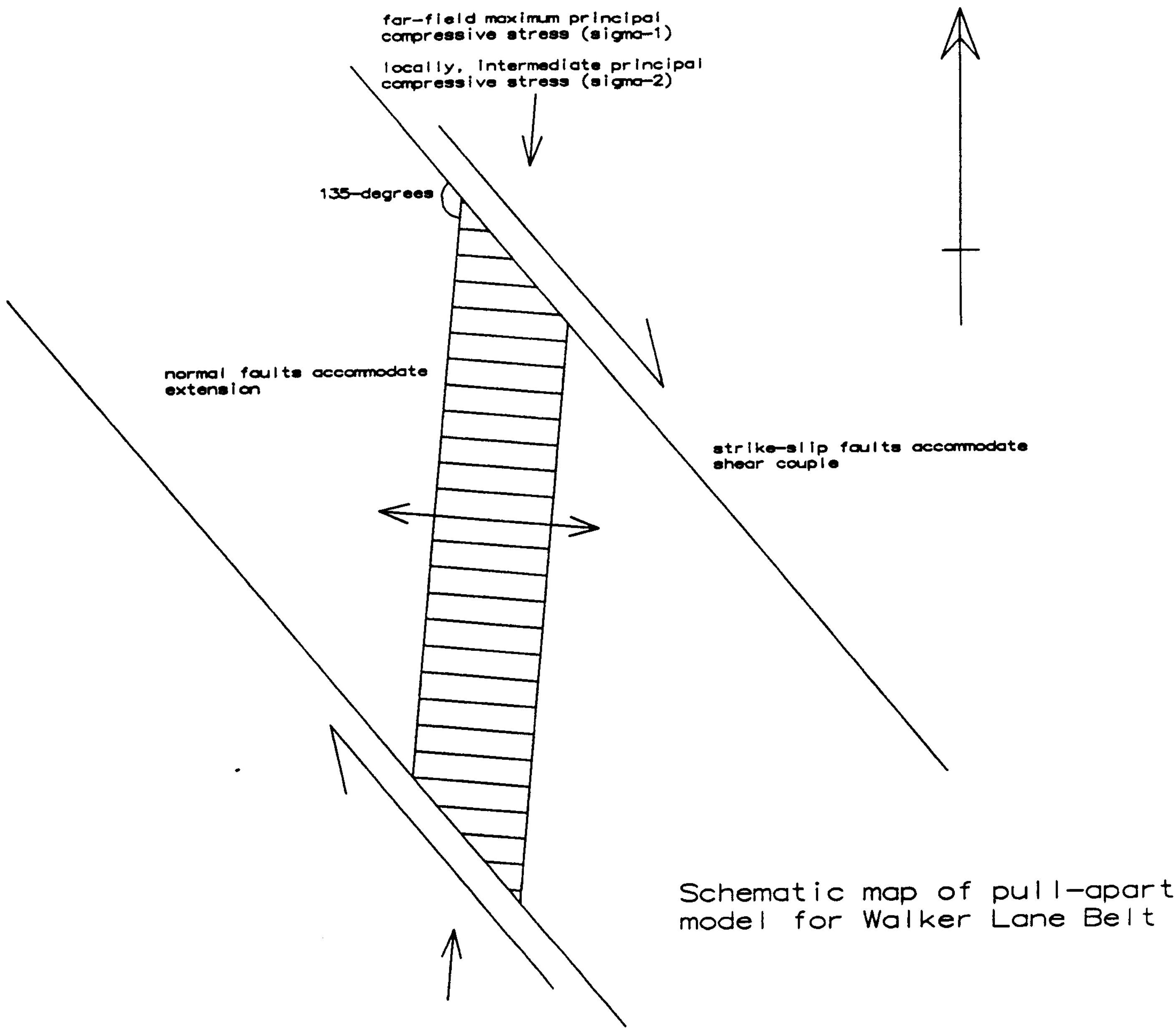


Figure 3-12. Schematic map of pull-apart model for Walker Lane (see, for example, Burchfiel et al, 1987). The orientations fit a simple shear model for the development of extensional faults within the zone of distributed shear. Yucca Mountain would be situated within the extending (cross hatched) corridor.

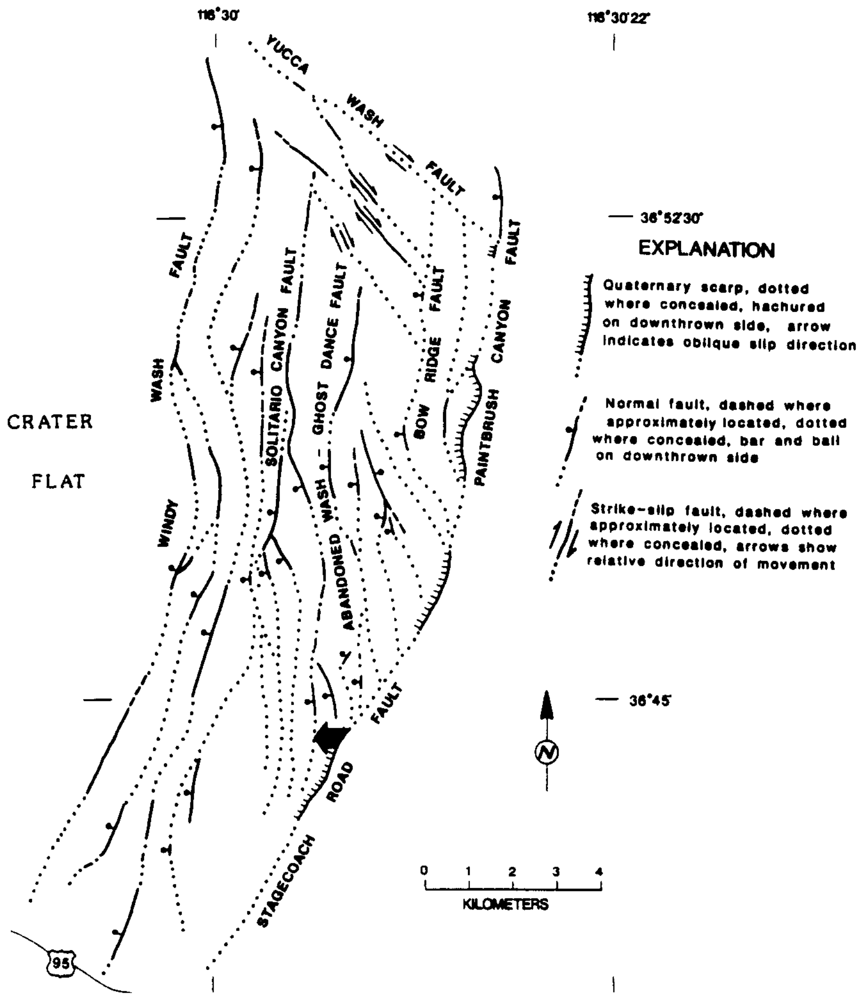


Figure 3-13. Map of faults at Yucca Mountain (Scott, 1990). The orientations and styles are very similar to the schematic simple shear model of pull-apart shown in Figure 3-12.

3.7.2 Strain Compatibility and Scale Effects

Deformation features exist across several orders of scale magnitude, from crustal-scale faults such as the San Andreas (10s–100s km) to atomic-scale crystal dislocations (2-3 Angstroms). Only approximately two orders of scale magnitude can be represented on any one graphical depiction of a deformation feature. For example, the average geological cross-section can reasonably show faults that are comparable in extent with the size of the section, and other, smaller faults that accommodate displacements that are approximately one tenth of the extent of the section. Smaller displacements become unresolvable and larger displacements do not fit on the section. Fault displacements vary along faults and from fault to fault within a given system. This variation gives rise to compatibility problems that are not resolvable at the scale of a normal cross-section (Walsh and Watterson, 1991). In reality, this compatibility "problem" is solved by the development of strain features below the level of resolution of the cross-section or map, and will thus appear "ductile." These take the form of small-scale faults, joint-fractures, or crystal scale dislocations. In most extensional systems, small faults and joint-fractures will be the dominant mode of "ductile" accommodation.

Yucca Mountain is known to have arrays of small-displacement, predominantly normal faults (Scott and Bonk, 1984; Scott, 1990). In order to fully characterize the three-dimensional form of the major faults at Yucca Mountain, it is necessary to integrate the contribution of these small-scale features into the total strain pattern. This is especially important in light of the influence that such fractures may have on fluid flow through the rock mass of Yucca Mountain.

4 DISCUSSION

4.1 SECOND-GENERATION SECTIONS

Existing second-generation cross-sections of Yucca Mountain (Young et al., 1991; Young et al., 1992) represent the best available interpretations of the faults that underlie the area. They are based on all relevant surface and borehole geological data, and they are compatible with seismic reflection data from a nearby survey (Morris et al., 1992). These interpretations assume vertical shear as a deformation mechanism for the area and provide good explanations for the observed rollover geometries at Yucca Mountain. More elaborate interpretations involving, for example, multiple detachments both in depth and chronologically, are permissible (from the data), but applying the principle of efficiency formulated by Sir William of Occam ("Occam's Razor"), the simplest hypothesis consistent with the data is preferred.

4.2 LISTRIC FAULTS VERSUS DOMINO BLOCK

The debate over the applicability of listric normal faults rather than domino block deformation to extensional terrains has appeared in the literature for several years (Lister and Davis, 1989). In the case of Yucca Mountain, the question can be distilled to two considerations: can the proposed fault system explain (i) true rollover (increasing counter-dips into the fault zones), and (ii) variable dips from fault block to fault block. Thus far, the existing domino models and reasonable hybrids of them are unable to satisfy these requirements. In addition, the multiple (chronological) detachment model proposed by Lister and Davis (1989) to generate apparent dominoes from listric fault systems is inappropriate because of the small amount of Tertiary extension at Yucca Mountain (10 percent).

Model experiments show that although domino block formation is common (Vendeville et al., 1987), the thicker the deforming layer, the more likely that listric fault geometry will form. The same experiments also show that there is a relationship between the spacing of major faults and the thickness and strength of the deforming layer. This provides an interesting avenue for potential research: it may be possible to check depth to detachment estimates by an independent method based on the spacing of major faults.

5 CONCLUSIONS

Conclusions based on analyses of alternative geometric models of faulting and associated hangingwall deformation are as follows.

5.1 DEFORMATION MECHANISMS

- Vertical shear: The primary reasons for choosing vertical shear as a viable deformation mechanism for Yucca Mountain are: the occurrence within the hangingwalls of the faults of networks of subvertical, small-displacement faults and the ability of this method to explain true rollover (increasing counter-dip) into the major fault zones.

- Flexural slip: The currently available geological data does not permit this mechanism to be ruled out, although there is no strong evidence for it.

- Slip-line: There are no geometrical objections to the use of the slip-line mechanism; however, it does imply a degree of ductility throughout the hangingwall for which there is no direct geological evidence.

- Simple domino: Field data published by Scott and Bonk (1984) clearly shows that different fault blocks at Yucca Mountain have different dips and that there is well-developed "rollover" within each block. These observations cast doubt on the utility of simple domino models for Yucca Mountain. A final, powerful diagnostic test for the applicability of domino style faulting to Yucca Mountain may be provided by improved knowledge of the accumulation history of the Tertiary pyroclastic sequence: the requirement that domino systems must have linked fault motion precludes the possibility of variable growth across the area; thus, if variable growth is observed, the domino model can be rejected.

- Hybrid domino: Although it is possible to construct sections based on the hybrid models that represent the large-scale characteristics of Yucca Mountain's structure, the same objections that apply to simple dominoes also apply here.

5.2 EFFECTS OF GROWTH

- Vertical and oblique shear: Growth superimposed on vertical or oblique shear systems, and unrecognized by the observer, will not affect fault shape predictions that are based on shallow or surface geology, provided that good estimates of footwall cutoffs for the key horizons can be made. However, estimates of overall extension will be in error by an amount that is related to the total amount of growth that has occurred.

- Flexural slip: In the case of unrecognized growth superimposed on a flexural slip system, unless the full growth history can be obtained (e.g., from seismic reflection studies or drilling), serious errors will be made in the prediction of fault trajectories from shallow or surface geological data.

- Slip-line: Growth superimposed on a slip-line system, and unrecognized by the observer, will not affect fault shape predictions that are based on shallow or surface geology, provided that good estimates of footwall cutoffs for the key horizons can be made. However, estimates of overall extension will be in error by an amount that is related to the total amount of growth that has occurred.

- Domino: Growth horizons superimposed on dominoes will have lower dips than the pregrowth rocks; thus, restoration based on these dips will underestimate the total rotation, and thus, underestimate the overall shortening. Fault orientations can, however, be constructed accurately.

- General: It is very likely that the faults at Yucca Mountain were active during accumulation of tephra. The net effect of this, regardless of actual or assumed deformation mechanism, is that the overall estimate of extension based on shallow wells and surface geology is probably an underestimate.

5.3 CONTEXT-DRIVEN MODELS

- Detached cover: The rollover geometries developed at Yucca Mountain are consistent with listric faults that sole at depths that are deeper than the probable base-Tertiary unconformity for any realistic oblique shear angle; therefore, the detached cover model is not likely to produce good and reasonable interpretations. Until better information about the sub-surface geometries of faults and/or the depth of the base-Tertiary unconformity under Yucca Mountain is available, detached cover models should be considered as speculative and unsupported by data.

- Isostatic rebound: The Bare Mountain fault is likely to be a younger, deeper fault that has cross-cut the listric system underlying Yucca Mountain. Formation of the Bare Mountain fault is directly related to the isostatically driven rise of Bare Mountain in response to tectonic denudation.

- Pull-apart model: Pull-apart deformation at Yucca Mountain is the most likely model for the range-scale tectonic setting, and construction of cross-sections south of the mountain represent an important next step in characterizing the three-dimensional structural setting of the area.

- "Ductile" deformation: Yucca Mountain is known to have arrays of small-displacement, predominantly normal, faults. In order to fully characterize the three-dimensional form of the major faults at Yucca Mountain, it is necessary to integrate the contribution of these small-scale features into the total strain pattern. This is especially important in light of the influence that such fractures may have on fluid flow through the rock mass of Yucca Mountain.

6 RECOMMENDATIONS

The following recommendations are made regarding compilation or acquisition of data critical to resolution of key problems and uncertainties related to development and assessment of alternative conceptual models of tectonic deformation. The extent to which these data are available in the literature is not fully known at this time. It is virtually certain that available data will not be sufficient for development of definitive models, nor for rigorous assessment of conceptual tectonic models that may be developed in the near future.

- Acquire data relevant to understanding the growth and compaction history of Tertiary tephra accumulation and fault activity. These data are essential for modeling of faulting processes and history, and for determination of fault shape.

- Acquire data to constrain subsurface fault orientations. Reflection seismic and additional drilling may be the only way to add substantial data on subsurface fault orientation.

- Investigate the role played by small-scale normal faults in permitting strain accommodation around fault tips and between major faults. Field work ongoing at Yucca Mountain seems to be focusing more on mapping and measurement pertinent to this data need. Monitoring of this work and timely compilation of resulting data may provide additional valuable constraints on deformation mechanisms in the short term.

- Construct additional cross-sections through the southernmost part of Yucca Mountain using available data to attempt to constrain the three-dimensional characteristics of the Yucca Mountain system. This will be accomplished in an activity scheduled for FY93 in the Task 3 Operations Plan of the CNWRA Geologic Setting program element.

- Develop a more highly integrated and comprehensive cross section tectonic model of Yucca Mountain by extending the existing sections eastward across Fortymile Wash to about the vicinity of Little Skull Mountain, and westward across Bare Mountain to the vicinity of the Bullfrog Hills. It is necessary to consider tectonic models of Yucca Mountain simultaneously at various spatial scales to establish consistency of local models with regional relationships, and to assess implications of interpretations of faulting at Bare Mountain, within Crater Flat Valley and within the Fortymile Wash area.

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