2

EVALUATION OF COMPUTER-ASSISTED CROSS SECTION BALANCING METHODS FOR ANALYSIS OF SUBSURFACE FAULT GEOMETRY IN THE VICINITY OF YUCCA MOUNTAIN, NEVADA: A PILOT STUDY

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The purpose of this pilot study is to evaluate the usefulness of computer-assisted geological cross section balancing methods in the geometric and kinematic analysis of subsurface structures in the vicinity of Yucca Mountain, including underlying listric normal fault and detachment fault geometries and their relationships in a linked fault system. While some information is available on fault dips at the surface and trajectories or shapes of faults at shallow depths, deeper-level fault trajectories are often unknown and interpretations of the geometry of linked listric fault systems are not well-constrained at depth. However, data from field observations on fault dips at shallow depths, deformation related to fault block rotations, and hanging wall rollover folds can be used to provide geometric constraints on the underlying fault system.

Data from a published geologic map and cross sections of Yucca Mountain (Scott and Bonk, 1984) provided the initial constraints for the development of geometric models of deep subsurface structure. Using these constraining data, computer-assisted cross section balancing was undertaken to analyze the geometric and kinematic relationships between shapes of major faults, structural features in hanging wall blocks, and an assumed simple shear deformation mechanism within hanging wall blocks. Basic principles of geologic balance (i.e. - conservation of stratigraphic area and bed length), coupled with the initial assumption of a simple shear deformation mechanism in the hanging wall blocks of major faults, allowed evaluation of the internal consistency of the geological cross sections and prediction of fault shapes at depth.

This study demonstrates the usefulness of computer-assisted cross section balancing methods for analysis of subsurface fault geometry in the vicinity of Yucca Mountain. Based on the field observations incorporated and the assumptions applied for the cross section balancing analysis, a shallow (i.e. - less than 4 kilometers) detachment fault model with a nearly-vertical simple shear mechanism for internal deformation within the hanging wall blocks was indicated to be a viable, balanced two-dimensional geological cross section "model". There were also indications from the results of this study that any detachment surface to which the existing listric normal faults can be linked may lie at least 1 kilometer below the Tertiary-Paleozoic contact in the vicinity of Yucca Mountain, even though this contact is often interpreted to be the position of the detachment surface.

Internally consistent, balanced geological cross sections which incorporate a rational relationship between fault shape and resultant hanging wall geometry provide a fundamental framework for assessing potential hazards related to seismotectonic events, fault displacement, and volcanism as well as for addressing the influence of faulting and related fracturing on groundwater flow. The computer-assisted cross section balancing approach will provide information to assist NRC staff with independent review of geological models proposed for use in assessment of performance of the Yucca Mountain site. The information will also be useful for delineating gaps in the data base and for analyzing the validity of conclusions drawn about the geometric and kinematic relationships of subsurface structures in the vicinity of Yucca Mountain.

1. INTRODUCTION

The geological framework for Yucca Mountain, comprised by the varying lithologies and structural features of the site and site region, provides the natural system within which site suitability and performance will be assessed by the Department of Energy (DOE) for such important issues as faulting, seismicity, volcanism, ground water flow, and radionuclide transport. While the lithologic variations have been mapped and are relatively well understood in the broadest sense, the structural features are projected to depth mainly by interpretation from surface measurements and observations. Through the method of computer-assisted geological cross section balancing, subsurface fault geometry in the vicinity of Yucca Mountain can be analyzed, and more realistic assumptions can be made about the geometric and kinematic relationships of faulting at depth. Alternative structural geological cross section models of Yucca Mountain can be readily developed, examined, and refined by this computer-assisted cross section balancing method to assist in the analysis of subsurface faulting.

The internally consistent, balanced geological cross sections produced by this computer-assisted method, constructed to take into account the relationship between fault shape and geometry of hanging wall block structures, are fundamental for determining a realistic subsurface geological framework model for the Yucca Mountain site and site region. The geological framework model, in turn, provides input for determination of regional-scale tectonic models which represent deformation of the crust and show geological conditions that may influence the future response of the Yucca Mountain site and site region to changing stresses. Consequently, development of viable tectonic models for the region including Yucca Mountain also depends upon the geometric and kinematic relationships of structures analyzed by the cross section balancing method.

1.1 PURPOSE OF STUDY

The purpose of this pilot study was to demonstrate the utility of geological cross section balancing methods for the geometric and kinematic analysis of subsurface structures in the vicinity of Yucca Mountain. Specifically, it is shown that fundamental principles of structural balance can be used 1) to test two-dimensional structural interpretations for geologic validity; 2) to predict deep fault geometry from structural information obtained at or near the ground surface; 3) to predict the geometry of hanging wall fault blocks as they move along the underlying deep fault surface; and 4) to study the type of deformation to be expected in the vicinity of the repository due to movement on nearby faults.

1.2 OBJECTIVE AND GENERAL APPROACH

The main objective of this pilot study was to use existing published data to analyze the geometric and kinematic relationships of subsurface structure beneath Yucca Mountain. To accomplish this objective, cross sections through the Yucca Mountain area prepared by Scott and Bonk (1984) were analyzed for gross structural balance to test the compatibility of fault block geometries, interpreted fault shapes, and fault block deformation mechanisms inferred from their field observations. Based upon the general concept that geometric cross section "models" do

6

not necessarily represent unique solutions, the Scott and Bonk (1984) cross sections could logically be tested for geologic validity, internal geometric consistency, and structural balance by the technique of balancing and retro-deformation of the cross sections with the goal in mind of refining the interpretations about subsurface faulting.

The approach applied was to use computer-assisted cross section balancing methods with specialized computer software for the analysis. Balanced cross sections of subsurface features in the vicinity of Yucca Mountain were produced and restored to their pre-deformation states. "Benchmark" cross section models were created from the basic data for comparison with other cross sections and for use as a tool in testing future working hypotheses about the geometric and kinematic relationships of subsurface structures in the vicinity of Yucca Mountain.

2. EXPLANATION OF THE CONCEPT OF "BALANCED CROSS SECTIONS"

All cross sections through extensional basins or compressional thrust belts record the final stage of a complex structural history which may have included movement on faults and generation of folds. Whatever process deformed the rocks, at each stage of deformation the volume of any given rock unit will not usually have changed, so that any apparent volume changes require explanation. It follows, then, that it is possible to retro-deform, or reverse, the deformation of the structures seen in the section to produce a predeformation version (i.e. - restored-state) of the section in which the volume of each rock unit is the same as in the original state. An interpretation of the structure that allows restoration of the cross section to some predeformation state, without requiring unexplained changes in volume of any of the rock units, is called a balanced interpretation.

While a balanced cross section is not necessarily a unique solution, or even the rigorously correct "model" to use, a cross section that does not balance is almost certain to be incorrect. In general, if a structural interpretation is balanced, it is deemed to be an admissible solution, even though it may be non-unique. If the interpretation does not balance, and no reasonable explanation can be offered for the incompatibility between the deformed and restored-state sections, the interpretation is not admissible as a valid solution.

Cross sections are commonly used to depict the subsurface structure of geologic regions. Therefore, the two-dimensional balancing methods required for analysis of cross sections are relatively well-developed. Evaluation of a geological cross section for balance involves application of both specific geometric and kinematic principles and a set of assumptions about the nature of geologic deformation in the region of interest. The basic quantitative principles applied for balanced cross section construction and analysis are as follows:

1) conservation of solid mass

2) conservation of volume

3) conservation of area

4) conservation of bed length

5) conservation of bed thickness.

One fundamental principle applied for construction and analysis of balanced geological cross sections is that rock material is conserved during the deformation process. Therefore, rock material involved in any given deformational state of the cross section model must remain in the model both during restoration to an earlier state of deformation and during forward modeling to any later deformation state. Likewise, no rock material can be added during deformation. However, because there are geologic processes which can remove material from, or add material to, a deforming system, knowledge of these processes must be incorporated, when necessary, along with applicable geometric constraints in order to construct a balanced cross section or to evaluate other sections for balance.

Analysis of the cross section is undertaken, wherein the geometry of the geologic structures in the present-day deformed state is determined as precisely as possible, and the section is sequentially restored to progressively earlier deformation states. Since current understanding of deformation processes in the shallow crust indicates that the natural system must balance, the deformed state model must be retro-deformable to a series of geologically reasonable predeformation states. Reassembly of the undeformed state cross section model from the deformed state section generally involves the following steps:

1) removal of fault displacements

2) unfolding of folds

3) removal of syndeformational sedimentation

4) removal of effects of erosion

5) removal of effects of compaction

6) removal of products of igneous intrusion (if present)

7) recovery of distortional strain

8) accommodation of pressure solution.

A fundamental assumption in analysis of balanced geological cross sections is that the primary or net slip vector of the major faults lies in the plane of the section. This requirement for a basically plane strain condition for cross section deformation allows straightforward application of quantitative principles for balancing, restoration, and forward modeling. Cross sections can be examined for adherence to the basic principles, and a determination made as to the extent to which the section is balanced. A more powerful application, however, is to incorporate the principles in construction of cross sections that are initially balanced, and that can then be restored to a predeformation state or forward modeled to potential future deformation states in a balanced condition.

Geometric methods for construction and kinematic modeling of balanced cross sections in extensional terranes depend on simulation of deformation mechanisms that allow adherence to the basic principles and have a geologic basis related to the region of interest. Simulation of simple shear deformation in extensional terranes is an area-conserved technique, so that cross sections using this deformation mechanism that are restored from the deformed state to either an undeformed, or an intermediate, deformation state retain the same area. Similarly, cross sections that are forward-modeled to later, more advanced deformation states undergo no changes in area.

For an extensional deformation regime, the amount of rock material displaced by extension through movement of the hanging wall block along an underlying fault surface is exactly balanced by the area of the basin created at the trailing edge of the block (Fig. 1). The key concepts involved are: 1) the hanging wall block must collapse onto the fault surface to avoid opening an unstable gap, X, in the subsurface, and 2) the resultant deformation of the block creates a basin for sediment accumulation that has an area, Z, equal to the product of the extension and the thickness of the fault block (i.e., the hanging wall area, Y, moved out of the section). The concept of geometric balance requires that area be conserved as the hanging wall block changes shape to accommodate the shape of the fault surface at depth.

Three general geometric forms of simple shear deformation can be implemented such that the hanging wall behaves as though it were composed of a deck of cards (Fig. 2). During simple shear, the fault block changes shape by distributed shear displacement along an array of closely spaced slip surfaces. Both vertical and inclined simple shear planes are used to model the Yucca Mountain cross sections. Currently, no evidence is available that horizontal shear or layer-parallel shear are viable for these sections. Simple shear deformation requires that the two-dimensional cross section trajectory (i.e. - shape) of the underlying bounding fault and the shape of the deformed fault block be related by the geometry of the deformation mechanism. Given a specific simple shear plane orientation, the result of this relationship is that fault trajectories can be predicted from the deformed geometry of key geologic horizons in the hanging wall block (Fig. 3) and, conversely, fault block deformation can be predicted from known fault shapes and specified amounts of extension (Fig. 6).

Fault prediction using a vertical shear mechanism requires that three things be known about the shallow geometry of the structure (Fig. 3):

1) the rollover or fold geometry of at least one key geologic horizon in the hanging wall block

2) the position of the same key horizon in the footwall block

3) the portion of the fault that connects the two parts of the key horizon.

The unknown portion of the fault trajectory is computed by projecting the net displacement vector of a point on the key hanging wall horizon downward along the path of the vertical slip surfaces to the point where it intersects the known part of the fault (Fig. 4) This process is repeated in incremental steps until the fault trace is complete. The key assumption here is that the horizontal line marked "REGIONAL" in Figure 4 represents the initial undeformed shape of the folded horizon in the hanging wall block.

As slip accrues on the fault, any arbitrary initial bed point moves to a deformed state position which is the final bed point for a given increment of extensional displacement. For vertical shear deformation, the net displacement vector connecting these two points has the same slope as the underlying segment of fault. For inclined shear deformation (Fig. 5), the net displacement vector of a point on the geologic horizon is projected downward along the inclined slip surfaces and connected to the known portion of the fault. Computation of hanging wall folds (Fig. 6) from fault shapes is accomplished by measuring the orientation of some incremental segment of the fault (AB), projecting this segment upward until it intersects the "regional" at (a), and then posting the projected final bed point (b). The total deformed state shape of the hanging wall horizon is then drawn in by connecting all of the "b" points of the projected fault slip vectors.

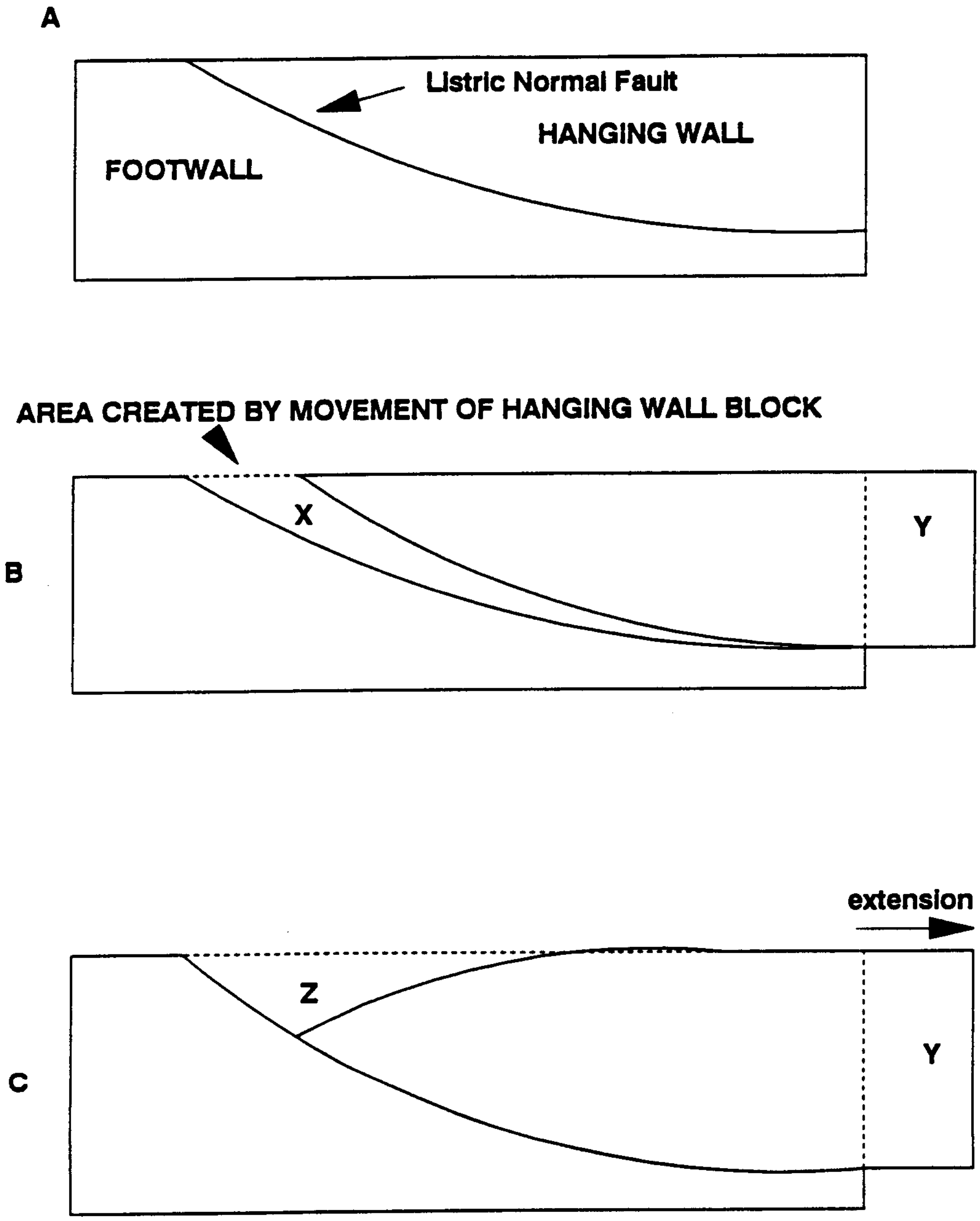
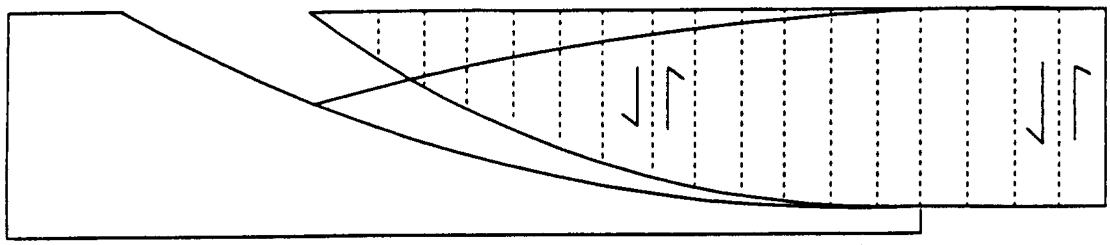
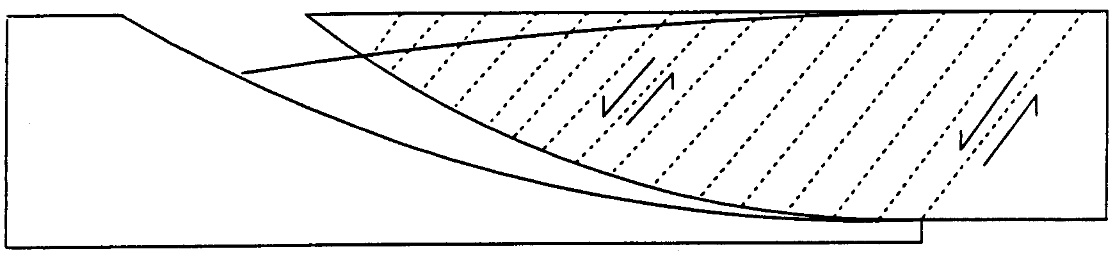


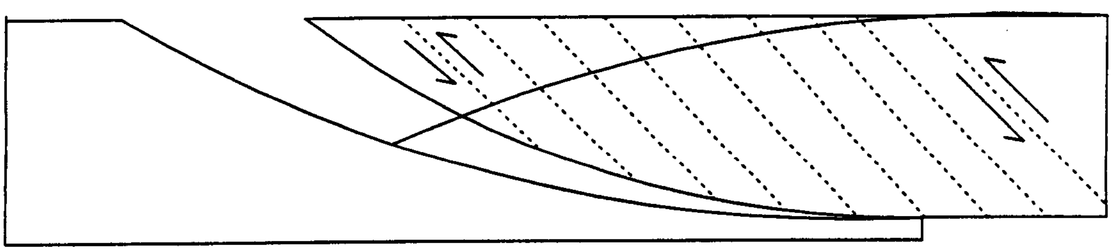
FIGURE 1. Area is conserved during simple shear deformation of the hanging wall block. The area created by extension of the model (X) is equal to the area moved out of the model block (Y) by slip along the listric normal fault. In nature, this area is accomodated by creation of a basin (Z). In this case, Z = X = Y.



A. VERTICAL SHEAR



B. ANTITHETIC INCLINED SHEAR



C. SYNTHETIC INCLINED SHEAR

FIGURE 2. General simple shear is modeled as the hanging wall deformation mechanism for the cross sections in this study. The simple shear mechanism replicates the behaviour of a deck of cards. So that as the hanging wall moves along the underlying fault, it accommodates its shape to that of the fault by slip along the array of parallel slip surfaces.

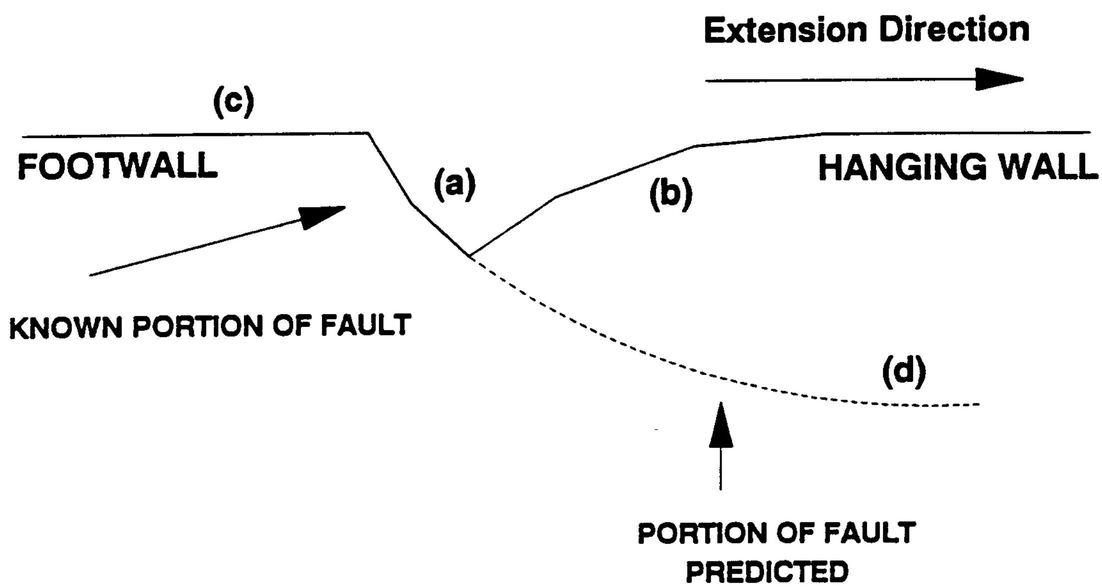


FIGURE 3. FAULT PREDICTION MODEL - Deeper level fault geometry can be computed from structural information observed at shallower depth or at the ground surface. In this case a shallow portion of the fault trajectory (a), the shape of the hanging wall rollover fold (b), and the position of the correlative horizon in the footwall (c) must be known to compute the deeper portion of the fault trajectory (d).

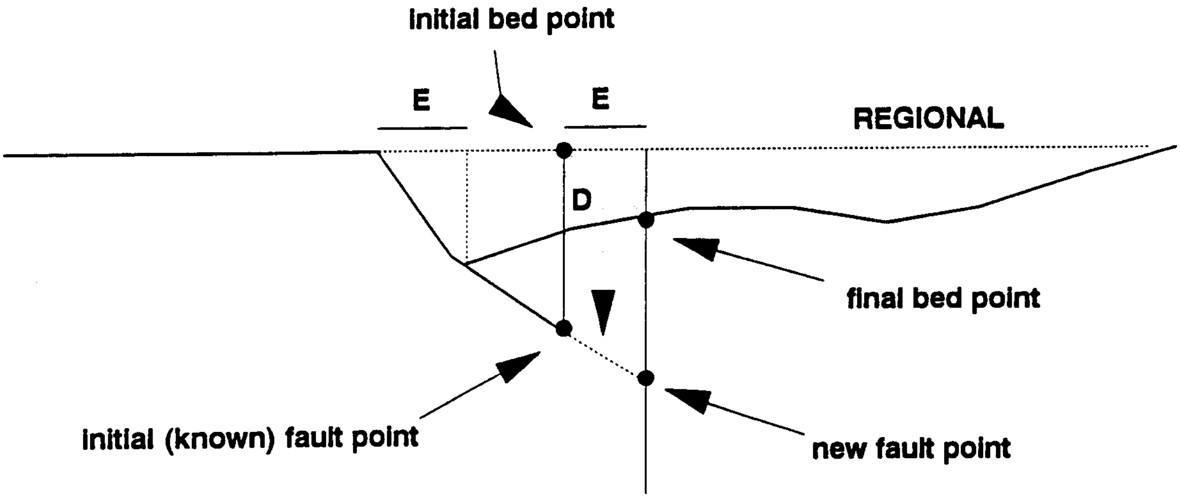


FIGURE 4. VERTICAL SHEAR FAULT PREDICTION - Fault trajectories are projected from the deepest known point by translation of the net displacement vector (D) of points on a key hanging wall horizon. D is projected downward along the path of the vertical slip surfaces until it intersects the known fault point. This procedure is repeated using some specified increment of displacement (E) to the point where the the hanging wall horizon returns to regional dip.

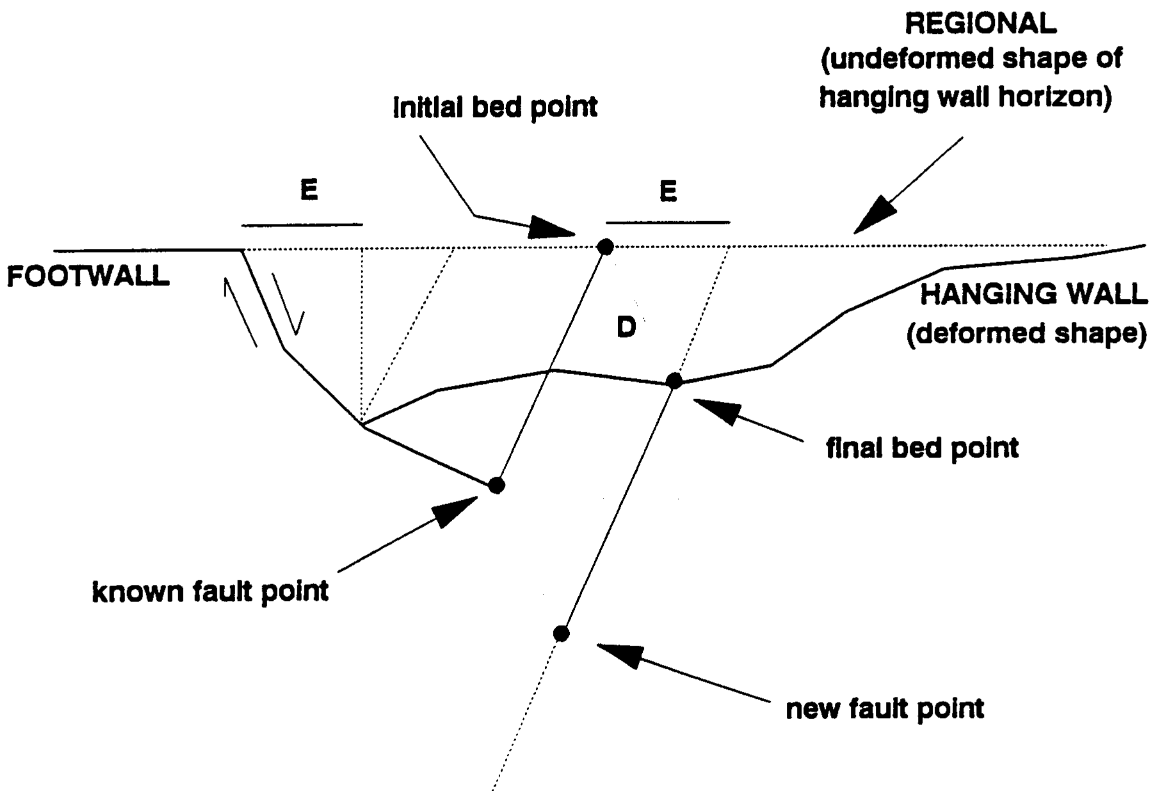


FIGURE 5. INCLINED SHEAR FAULT PREDICTION

The net displacement vector (D) of the deformed hanging wall horizon is projected downward along the inclined slip surfaces until the initial bed point intersects the fault trace at the last known point. The final bed point on the vector line then becomes the new fault point. This process continues in increments of E until the fault trace reaches a point below where the deformed hanging wall horizon returns to regional dip.

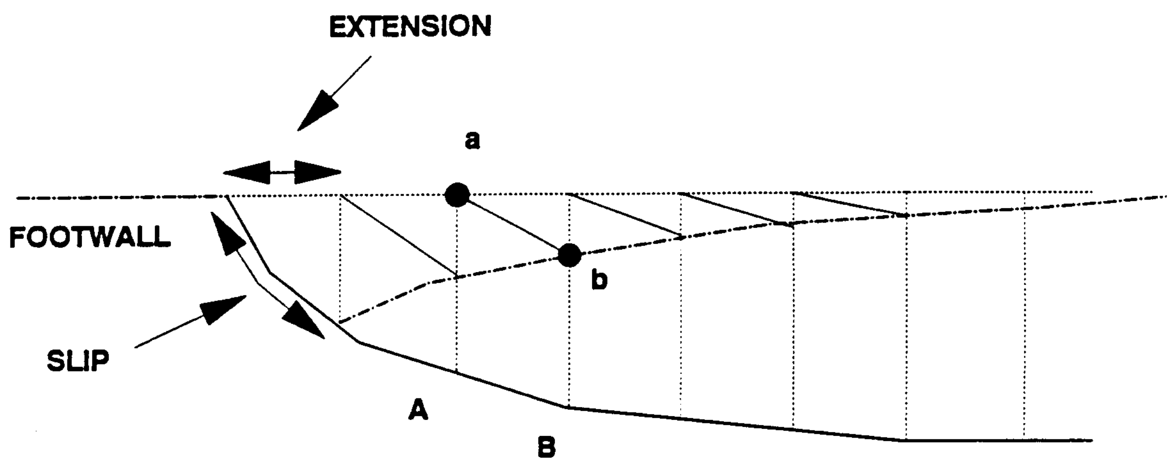


FIGURE 6. PREDICTION OF HANGING WALL FOLD SHAPE - Complete fault trajectories can be specified and resultant deformed state hanging wall geometry computed in a manner similar to fault prediction. The footwall position of the key horizon, the fault trajectory and the amount of slip or extension must be known.

3. TECHNICAL COMPUTING REQUIREMENTS

The ability to use computers for the cross section balancing makes it possible to accurately construct balanced sections, while greatly reducing both the time required for the construction and the potential for human error which exists when balancing is done manually. Because many more models can be constructed, evaluated, and compared than would be possible using manual techniques, interactive restoration and forward modeling are facilitated for use in the rapid testing of multiple working hypotheses and in sensitivity analyses of fault shape and slip history.

Two balancing programs were used in this project --- BSP and GeoSec. BSP (Balanced Section Program) was developed by Midland Valley Associates of Glasgow, Scotland, primarily for use in modeling extensional deformation and associated sedimentation in the North Sea/Viking Graben oil and gas exploration and production area of northwest Europe. The other software, GeoSec, developed by GeoLogic Systems of Boulder, Colorado, is intended for use in modeling both extensional and thin-skinned fold and thrust belt deformation.

3.1 DESCRIPTION OF BSP SOFTWARE

The BSP software is fully interactive and provides the capability to test interpretations through balanced section restoration. Structural models can be imported in digital form, digitized from a paper section or built step by step on the screen to highlight critical features of the geology.

The program currently uses vertical and inclined simple shear to model deformation of the geologic section. The simple shear mechanisms are especially appropriate for modeling extensional deformation, and also have some utility in modeling compressional deformation of certain thick Tertiary and Mesozoic clastic sections and in modeling ductile flow of salt or shale. Geologic models are produced, in which the user can add or subtract fault displacements to investigate structural evolution and associated stratigraphic effects. Key stages in the structural development of the area of interest can be rapidly identified.

The program enables the user to investigate the combined effects of the following geological features or processes:

* listric faults
* linked faults
* planar faults and detachments
* growth faults
* stratigraphic growth associated with faulting
* hanging wall folds
* duplex-imbricate zones
* basin development in extension
* tectonic inversion of extensional basins
* polyphase faulting.

An interactive graphics editing window allows editing of a model while the original model remains on the screen. The graphics editor makes it possible for the user to accomplish the following:

* add and delete bedding and portions of beds
* extend existing bedding
* insert new faults or modify fault shapes
* assign and reassign stratigraphic correlations
* specify bedding surfaces as active slip horizons (for use with the move-on-fault facility only -- not a flexural slip deformation mechanism)
* panning
* image zoom.

Movement on faults is allowed by the user pointing to each segment of the fault or slip surface as prompted by the program. The user is allowed to ask the program to join up beds across the fault or to impose an arbitrary slip on them. The amount of movement is therefore defined either in units (e.g. meters) or by electing to join beds across the fault. Bedding planes can be selected as slip horizons and both automatic and manual fault selection is allowed. The system can also accommodate conversion of reflection seismic data recorded in two-way travel time to depth for structural interpretation of the record section or as input to a more general structural model. The effects of compaction during deposition and decompaction for backstripping can be considered.

The BSP program is commercially available from Midland Valley Associates. CNWRA has a single CPU license for an IBM PS/2 Model 70. The program is also available for VAX/VMS mainframe systems, but requires at least a 4200 series Tektronix color graphics terminal for operation. Midland Valley Associates expects that a UNIX version for SUN workstations will be released by about February 1991. CNWRA plans to acquire a SUN version of BSP when it is released.

3.2 DESCRIPTION OF GEOSEC SOFTWARE

The GeoSec software can be used to construct, restore, and balance structural cross sections interactively in both compressional and extensional terranes. GeoSec is a more complex program than BSP, and is somewhat slower and less versatile in simple shear modeling of extensional structures. However, the system implements a more comprehensive and sophisticated set of deformation algorithms and modeling tools. Pertinent features of the program are as follows:

* easy input of well and surface data (stratigraphic tops and dips) and depth-converted seismic data

* well data input by either digitization from a previous section or as a computed directional survey

* built-in stratigraphic column

* modeling of flexural slip / flexural flow deformation
* projection of geometry to depth with either constant bed thickness or thickness gradients
* modeling of variable-thickness stratigraphy
* interactive restoration and balancing
* generation of cross sections from structure contour maps
* strain prediction and location of detachment level in folds
* bed length and area measurement
* computer-aided drafting and editing of sections
* presentation-quality color plots.

The GeoSec program was commercially released September 10, 1990, in a VAX/VMS version to run on the Digital Equipment VAXStation family of VMS workstations. GeoLogic Systems expects to release a UNIX version for the SUN sometime during the first quarter of 1991. CNWRA plans to acquire a SUN version of GeoSec when it is released.

4. ANALYSIS OF YUCCA MOUNTAIN CROSS SECTIONS

4.1 DATA BASE

The geological data used in this study consisted of the information presented on the geologic map and interpretive geological cross-sections of Yucca Mountain which were prepared and published by Scott and Bonk (1984). These data provided the information for development of geometric models of the deep subsurface structure through analysis of the geometric and kinematic relationships between fault shapes, structural features observed and measured in the hanging wall blocks, and an assumed simple shear deformation mechanism within the hanging wall blocks. Simple shear was assumed to be the Tertiary extensional deformation mechanism in the hanging wall blocks because, based on field evidence, Scott and Bonk (1984) indicated on their map and in their cross sections the existence of zones of small, relatively closely-spaced faults between the major fault traces.

Data from the careful field observations of Scott and Bonk (1984), incorporated into the geologic cross sections used for balancing, provided the following geometric constraints for the pilot modeling study: (1) Dip direction and amount for the major fault surfaces as measured in outcrop and (2) Rotation of layering and resultant rollover geometry (i.e. - dip reversals) in the hanging wall block adjacent to major faults as observed and measured in outcrop. Also, through personal communication with R. B. Scott in August 1990, additional information was provided on field evidence soon to be published (Scott, in press) about possible near-vertical or anastomosing deformation planes within the hanging wall blocks. Scott (personal communication, 1990) confirmed that the two geometric constraints noted above were observed and accurately measured in the field, as well as correctly represented in the geologic cross sections published by Scott and Bonk (1984).

4.2 KEY ASSUMPTIONS

The key assumptions made which allowed the application of the technique of computerized cross section balancing in the analysis of subsurface fault geometry in the vicinity of Yucca Mountain were as follows:

(1) The principle of geologic cross section balancing invoked was that areas and bed lengths are conserved during the deformation process. This concept of conservation of area and bed length is an "assumption" that is built into the computer program software, because it is a basic premise used in the construction of balanced geologic cross sections.

(2) The mechanism for internal deformation in hanging wall blocks adjacent to major faults was assumed to be simple shear. This assumption permitted a relatively straight-forward computation for modeling the geometric and kinematic relationships of the hanging wall block deformation which results from slip along major faults.

(3) No deformation occurred in the footwall block for any fault.

(4) The field data on orientation of major faults at the surface and geometry of the observed dip reversals were correctly depicted in the cross sections analyzed, and these data provided geologically reasonable constraints for the cross section balancing.

(5) Major faults merge to a single detachment surface at depth.

(6) Major fault zones were simplified as surfaces, rather than included as zones, in order to be able to analyze the displacements along those faults.

(7) The orientation of the undeformed marker horizon to which cross section B-B' from Scott and Bonk (1984) was restored, the base of the Tiva Canyon Member of the Paintbrush Tuff, was assumed to be horizontal.

(8) No out of section displacement.

4.3 APPROACH AND RESULTS

The geologic map and cross sections of Scott and Bonk (1984) comprised the data base used in the cross section balancing and analysis of subsurface fault geometry in the vicinity of Yucca Mountain (Fig. 7 & Fig. 8). Data from geological cross sections A-A', B-B', and C-C' of Scott and Bonk (1984) were digitized at GeoLogic Systems in Boulder, Colorado, for use in the GeoSec software package. These cross sections are located relative to Yucca Mountain as shown in Figure 8. For this pilot study, cross section B-B' was selected for the initial analysis and balancing because that section is more nearly perpendicular to the northeast-southwest strike of the major structural features at this location. Hence, this section is closest to the true dip section for those structures, and more accurately represents their dip angle for the modeling effort. Figure 9 illustrates present-day, deformed cross section B-B' as digitized directly from the section shown by Scott and Bonk (1984). Fault dips and the hanging wall dip reversals were transformed directly from the section into the digitized data base.

<u>Determination of subsurface fault trajectories and the detachment fault surface at depth for cross section B-B'</u>

First, subsurface fault trajectories were calculated by the GeoSec program for each of the three major fault zones shown in Figure 9, located east of Borehole 25a-1. (From west to east, these faults are named the Bow Ridge, Midway Valley, and Paintbrush Canyon Faults.) These initial fault trajectory "predictions" were based on the dip of each fault as determined at or near the surface; the geometry of the associated hanging wall dip reversals (i.e. - the hanging wall rollovers); and a simple synthetic shear plane orientation of 76 degrees, representing the internal deformation planes in the hanging wall block of each fault. The 76 degree synthetic shear plane orientation is generally indicated by information shown on the Scott and Bonk (1984) cross section. Because the geometry of the hanging wall dip reversals is directly related to the shape of the underlying fault when the simple shear internal slip mechanism is assumed, the fault trajectories can be determined using this method.

Next, the depth to a detachment fault surface compatible with the structural geometries indicated above was calculated. The depth of this compatible detachment surface was determined to be about 3.7 kilometers (Figure 10), a depth thought to be considerably deeper than the depth to the contact between Tertiary and Paleozoic rocks at this location, the position at which the detachment surface is predicted to lie by some workers. Therefore, it was decided to vary the orientation of the simple shear slip system in order to see what structural geometries would be compatible with a shallower detachment model. The work of Scott (1990) indicates that a vertical shear angle may be appropriate. By changing the internal slip surface from a 76 degree synthetic slip plane to a nearly-vertical one, it was found that a detachment surface located at a depth of about 2.3 kilometers (subsea) was defined (Figure 11). However, based on information from Borehole #UE25P-1, located about 5 kilometers east of the crest of Yucca Mountain (Fig. 8), 2 kilometers south of cross section B-B', and lying in cross section A-A', the depth to the Tertiary-Paleozoic boundary is approximately 1.4 kilometers (about 300m subsea). Consequently, this study may indicate that any detachment surface to which the listric normal faults could be geometrically linked at this location lie below the Tertiary-Paleozoic contact. This concept arises because the modeled linked listric fault system cuts through that contact before the dips of the faults shallow out.

During the analysis of the fault system using the near-vertical shear surface, a detachment fault was interpreted to be present east of the Paintbrush Canyon fault and added in order to account for the dip of the stratigraphic units in the footwall block of the Paintbrush Canyon. There is no direct evidence of a fault in Fortymile Wash, however, the fault is required to balance the footwall of the Paintbrush Canyon fault. The result of varying the dip of the slip surface indicated the sensitivity of the detachment fault model to the orientation of the internal slip plane.

Construction of balanced cross section B-B'

For the attempts at balancing cross section B-B', fault trajectories were merged into the detachment fault at depth, resulting in the construction of a linked listric detachment fault system for section B-B'(Fig. 12). Once the linked detachment fault system was constructed, cross section B-B' was used to model movement of the linked fault system and to determine what combination of subsurface structures produced geometric balance of the section. It was determined that a "shallow" (i.e. -less than 4 kilometers) detachment model would be selected for the balancing exercise, rather than a "deep" (i.e. - around 6 kilometers) detachment fault model. This determination was made because the detachment surface is thought by some workers to lie at or near the Tertiary - Paleozoic contact in this area. By exercising the capability of the cross section balancing method to readily develop and examine alternative geological models, the interpretation of a "shallow" detachment fault surface could also be analyzed to see if it is compatible with data from field observations.

The cross section was analyzed for balance by attempting to restore each of the hanging wall blocks to an undeformed, pre-faulting state. The restoration was accomplished by moving each hanging wall block along its underlying fault in an attempt to match hanging wall and foot wall stratigraphy across the fault. The base of the Tiva Canyon Member of the Paintbrush Tuff was the stratigraphic "marker horizon" to which the section was to be restored, so that this unit would be brought back to its horizontal, undeformed state by the restoration process if the cross section were balanced.

When restoration was undertaken using the 76 degree synthetic shear surface in conjunction with the "shallow" detachment system described above, the Tiva Canyon Member did not return to an undeformed state (Fig.13). Consequently, section B-B' did not balance when this combination of structural features was modeled in the hanging wall blocks of faults, indicating that some part of the system was probably not accurately represented. When the balanced listric fault model was combined with a near-vertical shear surface, however, the "marker horizon" did restore to an undeformed, pre-faulting state (Fig. 15), indicating that this combination of structural features modeled at depth was geometrically and kinematically compatible with the field observations of Scott and Bonk (1984). In actuality, the restoration analyses described above involved construction of two "alternative" fault models for Yucca Mountain, one of which was selected based on the fact that it balanced and, consequently, represented the field observations more accurately than the other.

In addition to being able to restore the cross sections by removing the deformation, after a balanced section has been constructed, it is possible to forward-model the cross section from any point in time to investigate variations in hanging wall deformation geometry with continued incremental slip on the constructed underlying fault array. This approach allows iterative analysis of the linked relationships between the subsurface structures in the vicinity of Yucca Mountain both in time and in two-dimensional space.

Initial Analysis of Section A-A'

Some preliminary analysis has also been done on section A-A' (Fig. 8 and Fig. 16). This section runs through bore hole UE25P-1, in which Carr and others (1986) have picked the contact between the base of the Tertiary volcanic rocks and the top of the Paleozoic section. The depth of this contact in the bore hole is about 1244 meters. This base Tertiary unconformity is an important structural and stratigraphic horizon because it is a regional low-angle fault surface (Maldonado, 1990). In the Bull Frog Hills, and perhaps in the Calico Hills, the Tertiary volcanic rocks have detached from the Paleozoic section by slip along the unconformity surface. Scott and Bonk (1984) and Scott (1990) suggest that this surface is also a detachment below Yucca Mountain. However, vertical shear balanced fault trajectories for the Fran Ridge and Paintbrush Canyon faults project through this horizon at a steep angle (Fig. 17). Vertical shear restoration of the Fran Ridge, Paintbrush Canyon, Bow Ridge and Solitario Canyon faults indicates that the total linked fault detachment system constructed for this model is close to being balanced (Fig. 18). A linked fault detachment system was also constructed to go through the location of the base Tertiary contact in the UE25P-1 bore hole (Fig. 19). The low-angle detachment was constructed to be compatible with the interpretation of Scott (1990). This section does not restore well using vertical shear deformation. More work is required to test the range of shear angles that may be indicated by the field work of Scott (1990). At this time though, it is not possible to conclude that the Yucca Mountain section is detached at the base of the volcanic section.

4.4 SUMMARY OF PRELIMINARY OBSERVATIONS

The following preliminary observations resulted from the pilot study:

(1) The study confirmed the importance of data obtained from field observations on faults and their associated structures. These data provided geologically realistic constraints for the cross section balancing approach to analyzing the geometric and kinematic relationships of subsurface faulting in the vicinity of Yucca Mountain.

(2) A "shallow" (i.e. - less than 4 kilometers) detachment fault model using a 76 degree synthetic simple shear mechanism for internal deformation within the hanging wall blocks of faults did not produce a balanced cross section for B-B'. An alternative "shallow" detachment model using a nearly-vertical internal deformation mechanism did produce a balanced cross section, however.

(3) There are indications from this preliminary study that any detachment surface to which the listric normal fault system could be linked at depth may lie at least 1 kilometer, or more, below the Tertiary-Paleozoic contact in the vicinity of Yucca Mountain, even though this contact is often interpreted to be the position of the detachment surface.

(4) Alternative geological models were readily developed and examined using the computerized cross section balancing method for analyzing subsurface faulting at Yucca Mountain. Forward modeling of balanced cross sections can be used to analyze the linked, two-dimensional relationships between the subsurface structures at Yucca Mountain as they may vary in time.

(5) The ability to use computers for the cross section balancing made it possible to accurately construct balanced sections and examine alternate cross section models, while reducing the time required and the potential for human error which exist when the balancing is done manually.

(6) This independent modeling effort, if extended and continued, will assist the Nuclear Regulatory Commission (NRC) in the review of the work planned by the DOE for geological characterization of the site and site region and for assessment of site performance. The computerized cross section balancing approach will provide state-of-the-art information, based on existing field data, which can be used as a yardstick for independently assessing the representativeness of "geological framework" models proposed for use in assessment of site performance; for denoting gaps in the existing data base; and for analyzing the validity of conclusions drawn about the geometric and kinematic relationships of subsurface structures in the vicinity of Yucca Mountain.

25

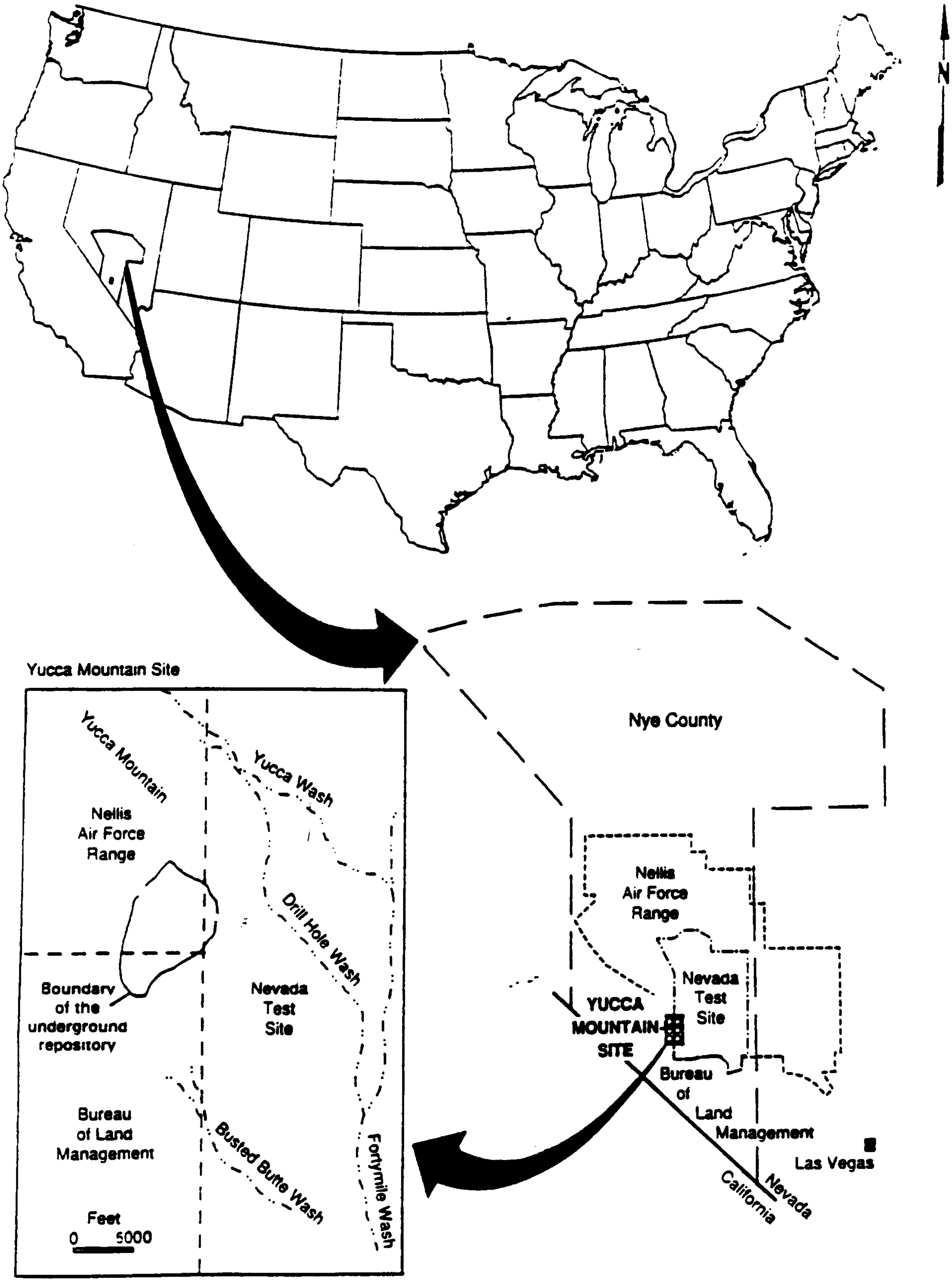


FIGURE 7. Location map of the Yucca Mountain area.

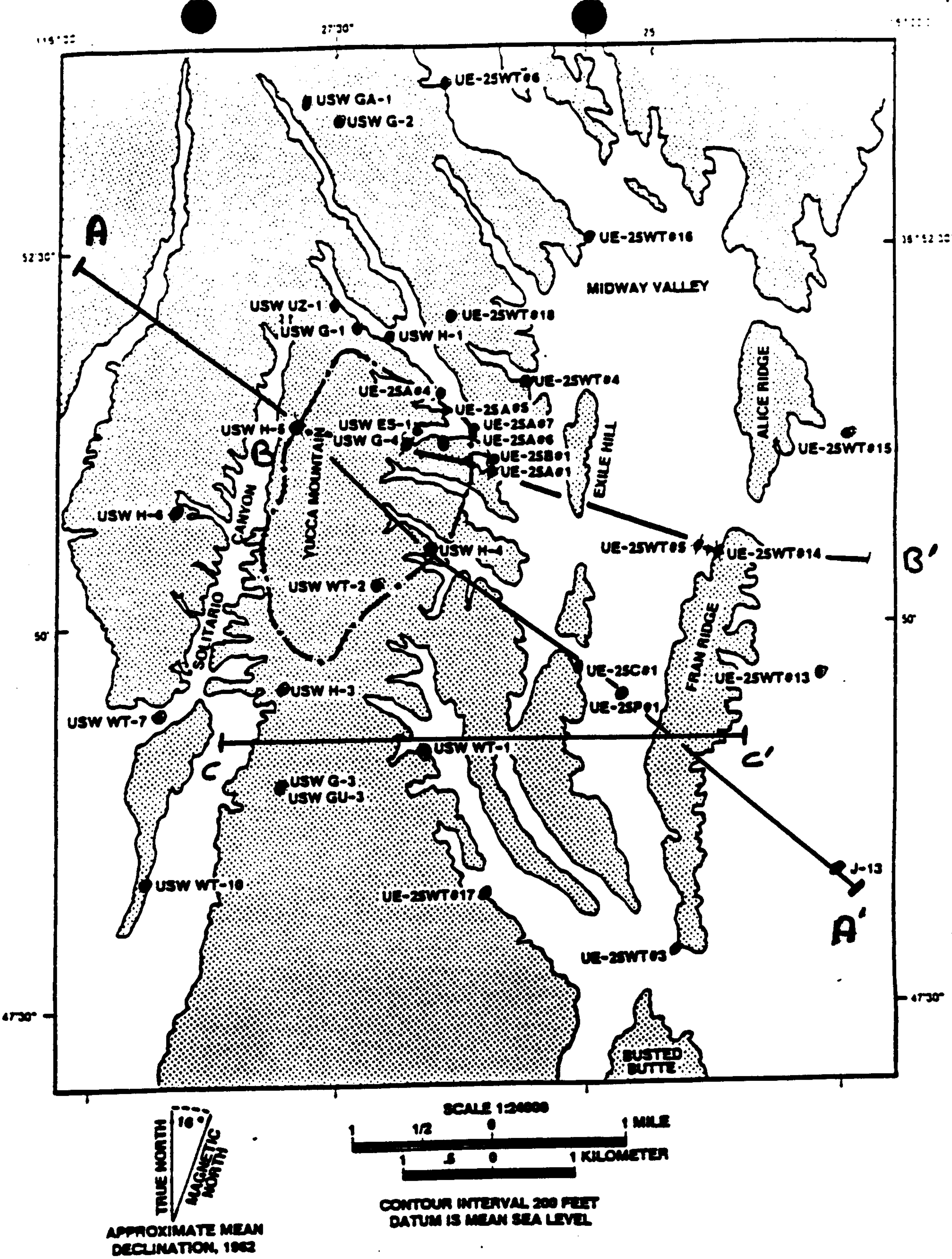


FIGURE 8. Map of Yucca Mountain and vicinity (bedrock stippled) showing approximate drill hole locations, proposed repository and cross section locations from Scott and Bond (1984).

FIGURE 9. Initial present-day (deformed-state) interpretation of section A - A' from Scott and Bonk (1984). This section was digitized directly from the published section.

SECTION B–B': ORIGINAL PRESENT–DAY INTERPRETATION

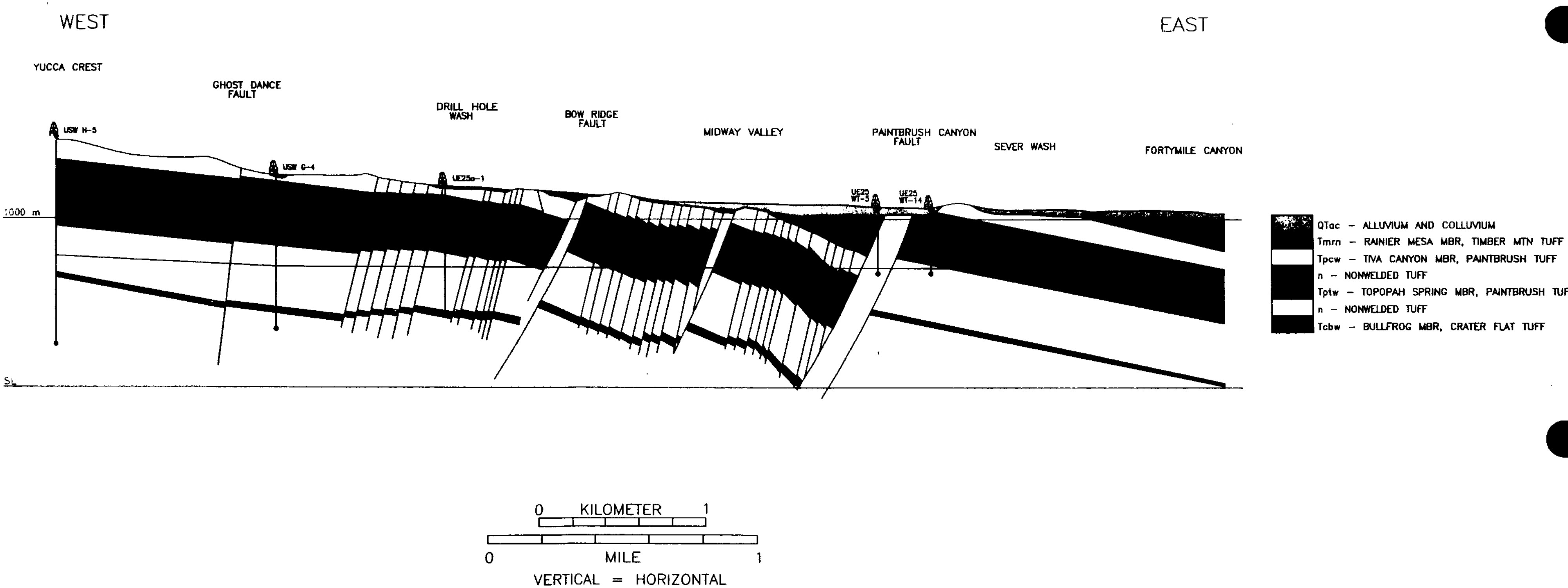
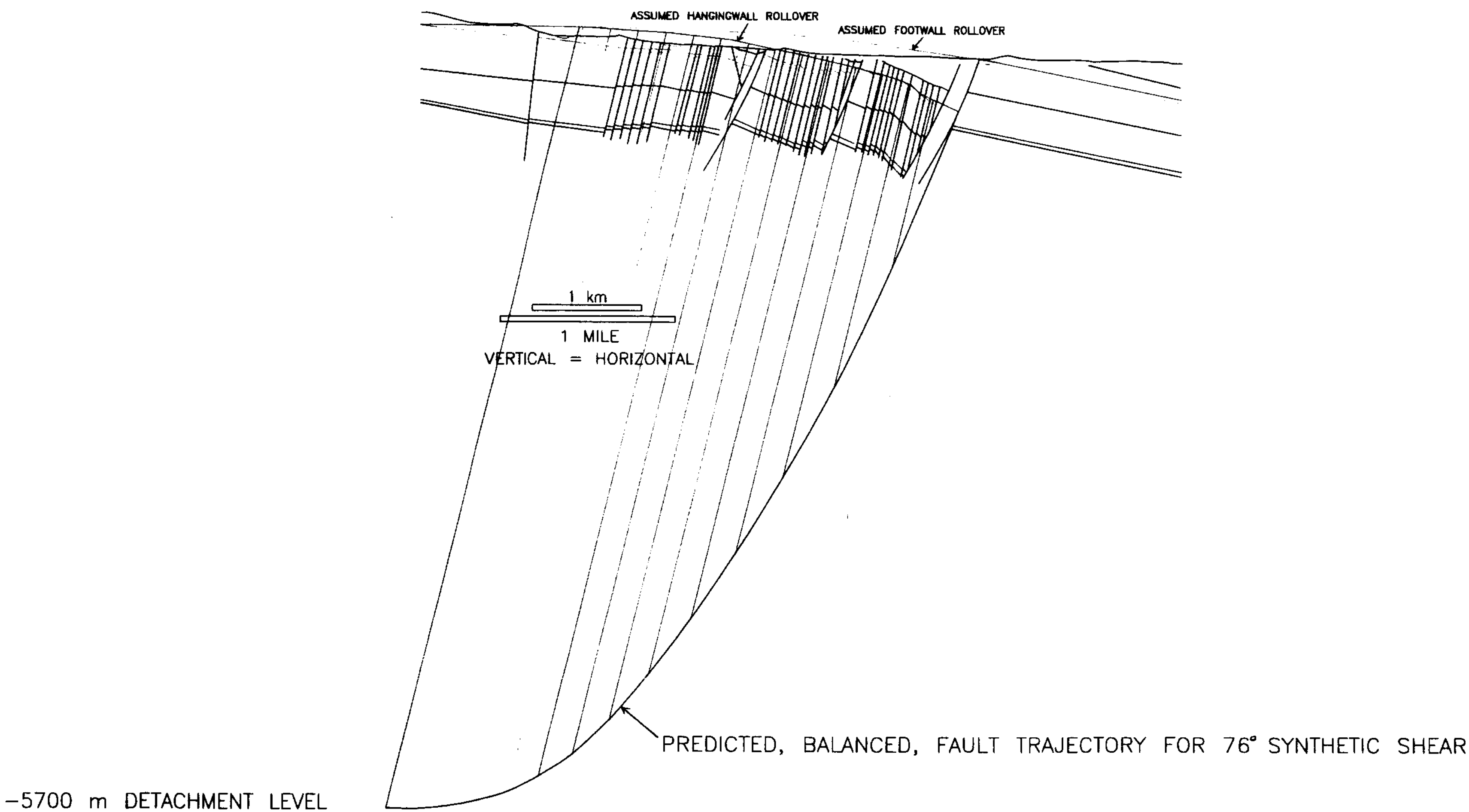


FIGURE 10. Prediction of balanced fault trajectory for the Paintbrush Canyon fault using 76 degree synthetic shear deformation. This shear angle matches the dip of the small closely spaced faults within the hanging wall fault blocks. We assume that these small faults are the deformation mechanism of the fault block and that deformation is occurring by simple shear along these surfaces. The fault trajectory is computed so that the hanging wall block of the Paintbrush Canyon fault will restore to its footwall.

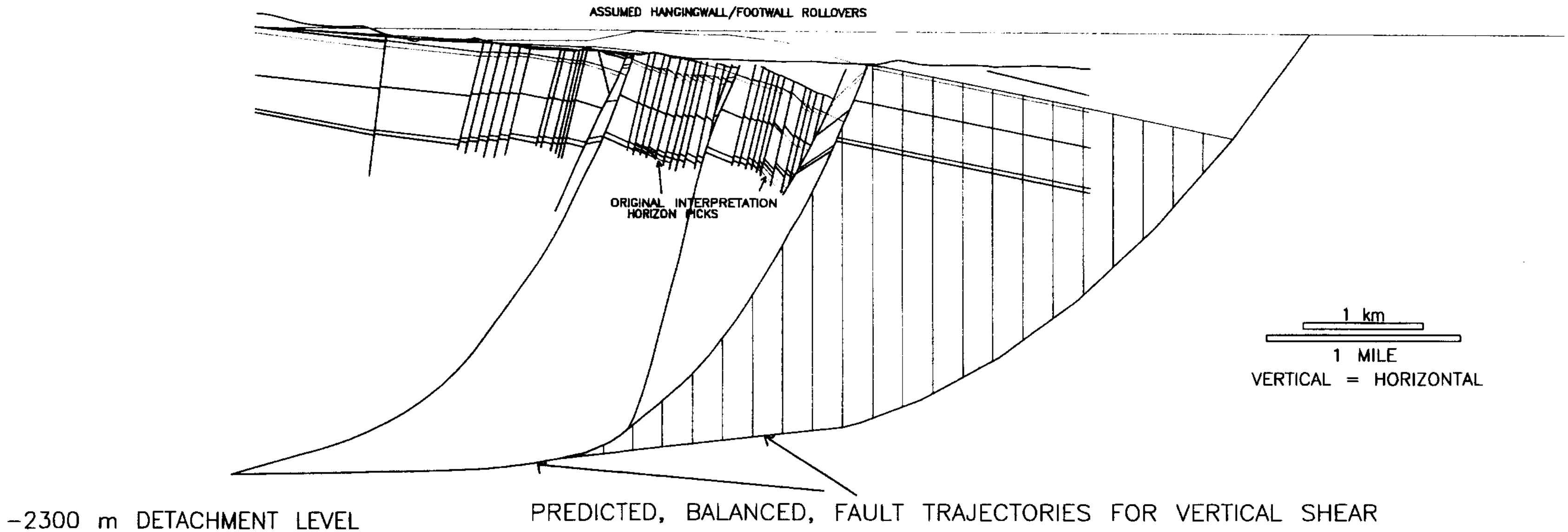
SECTION B–B'



ASSUMED HANGINGWALL ROLLOVER
ASSUMED FOOTWALL ROLLOVER
1 km
1 MILE
VERTICAL = HORIZONTAL
PREDICTED, BALANCED, FAULT TRAJECTORY FOR 76° SYNTHETIC SHEAR
−5700 m DETACHMENT LEVEL

FIGURE 11. Prediction of balanced fault trajectories for the Paintbrush Canyon, Midway Valley and Bow Ridge faults using vertical shear deformation. The un-named fault to the east of the Paintbrush Canyon is added to restore the footwall of the Paintbrush Canyon fault. The location of this fault corresponds approximately to the shallowing low-angle detachment of Scott (1990).

SECTION B–B'



ASSUMED HANGINGWALL/FOOTWALL ROLLOVERS
ORIGINAL INTERPRETATION HORIZON PICKS
1 km
1 MILE
VERTICAL = HORIZONTAL
-2300 m DETACHMENT LEVEL
PREDICTED, BALANCED, FAULT TRAJECTORIES FOR VERTICAL SHEAR

FIGURE 12. Construction of shallow low-angle detachment model. This model is built to approximate the detachment model of Scott (1990).

SECTION B–B': REVISED PRESENT–DAY INTERPRETATION (SHALLOW DETACHMENT)

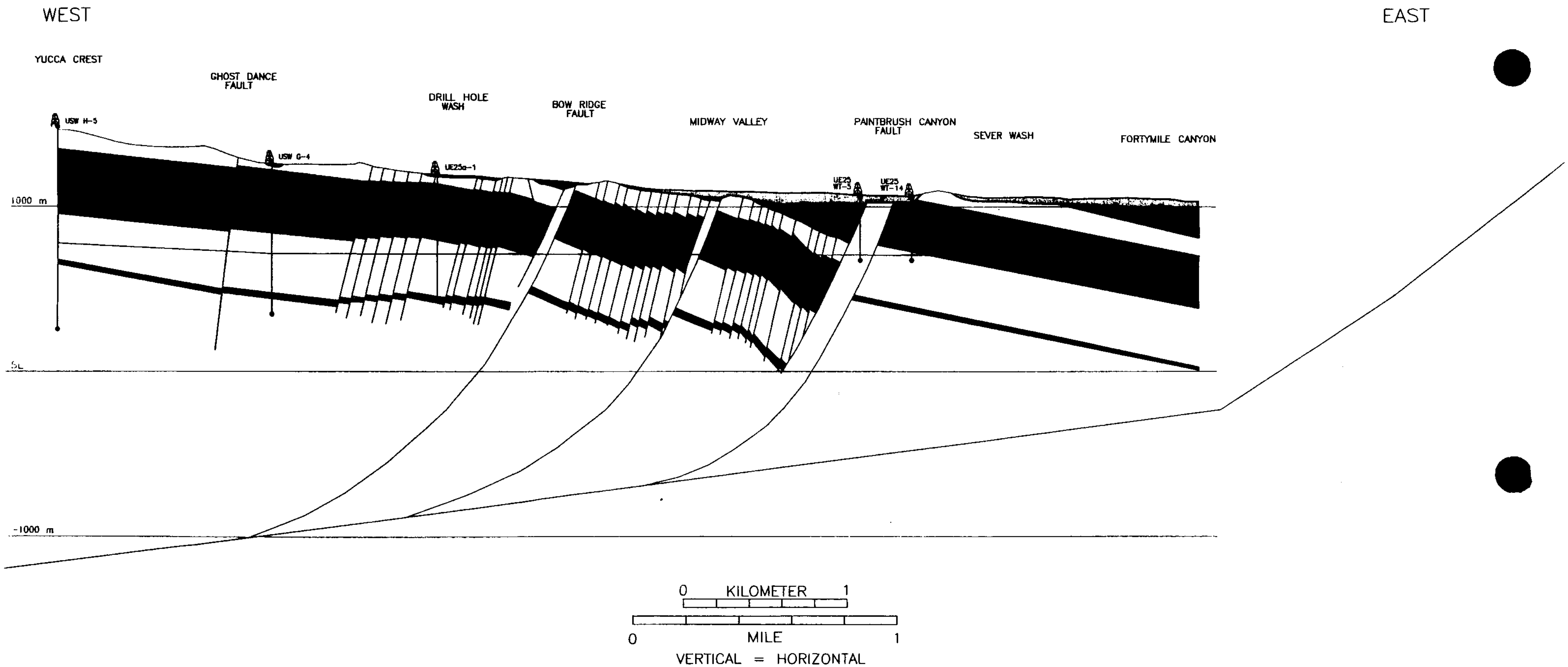


FIGURE 13. Restoration of Fig. 12 to the base of the Tiva Canyon (approx. top of Topopah Spring Member of the Paintbrush Tuff) using 76 degree synthetic shear deformation. The section will not restore and is very much out of balance. This indicates that the low-angle detachment model is not compatible with deformation along the small fault array as drawn. The problem could be with the fault array, the low-angle detachment geometry or both. Additional work is required to identify the specific reason that this section will not balance.

SECTION B–B': TIVA CANYON MEMBER RESTORATION
(REVISED INTERPRETATION, SHALLOW DETACHMENT, 76° SYNTHETIC SHEAR MODEL)

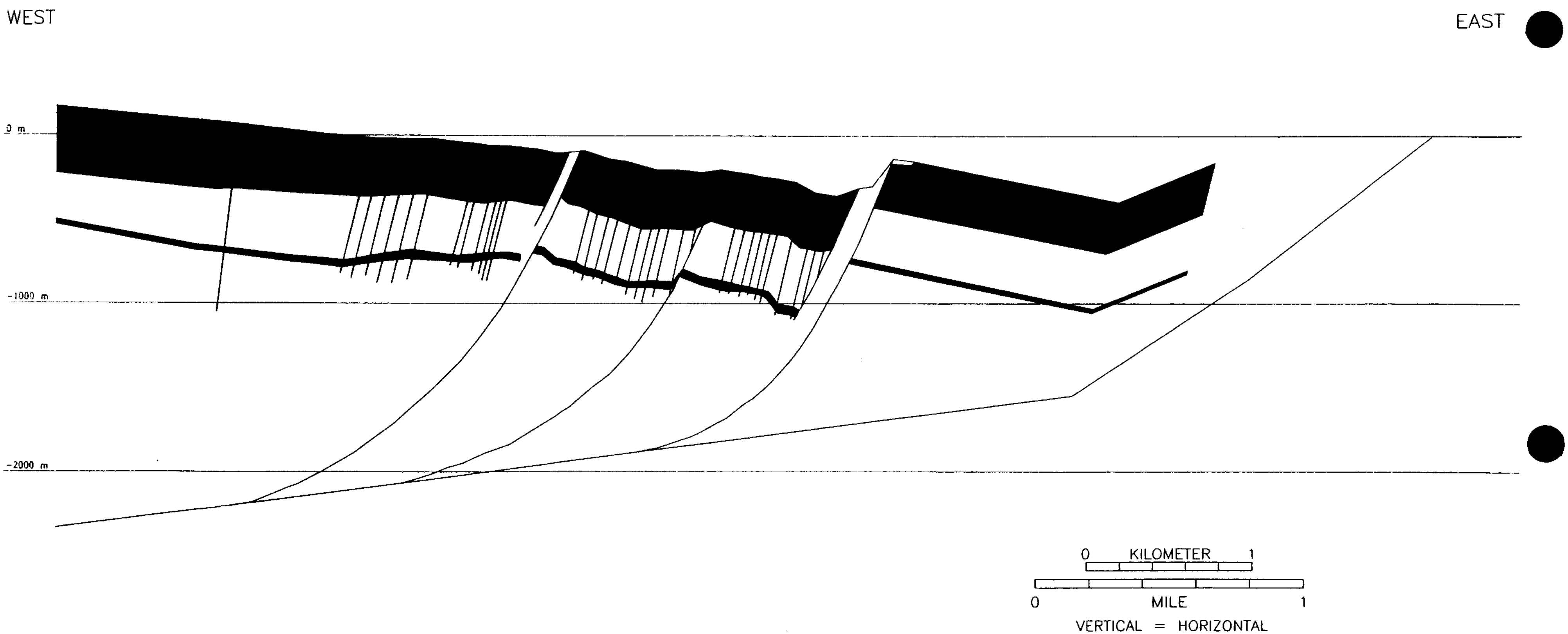


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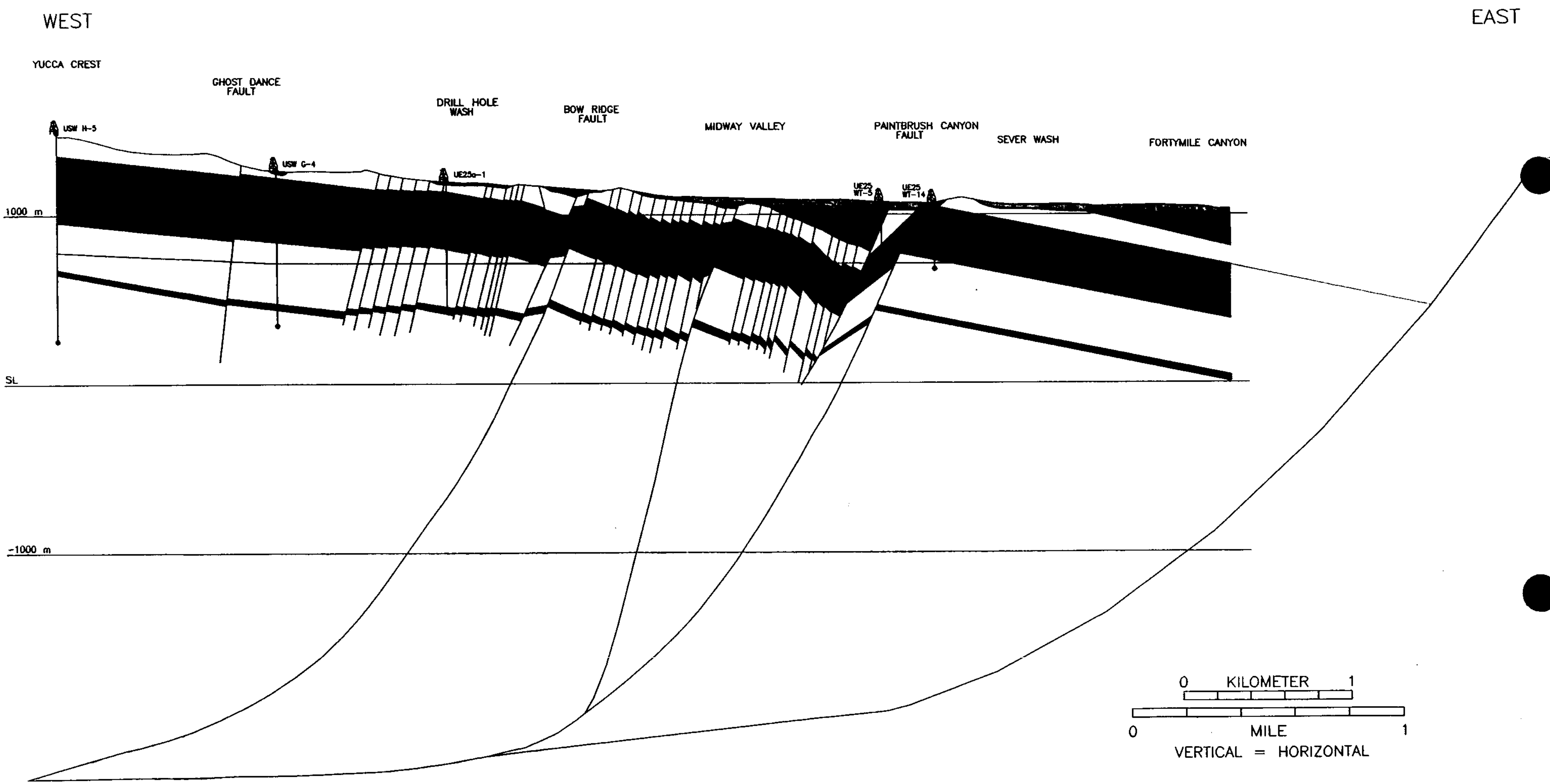
FIGURE 14. Construction of linked listric fault, low-angle detachment model using vertical shear fault predictions. Additional work by Scott (1990) indicates that the small fault zones may be better modeled as vertical simple shear. The small faults may actually occur as a complex anastomosing fabric with net slip averaging to vertical. This section is essentially a first step in exploring the possible suite of balanced solutions of Yucca Mountain structure based on field data.

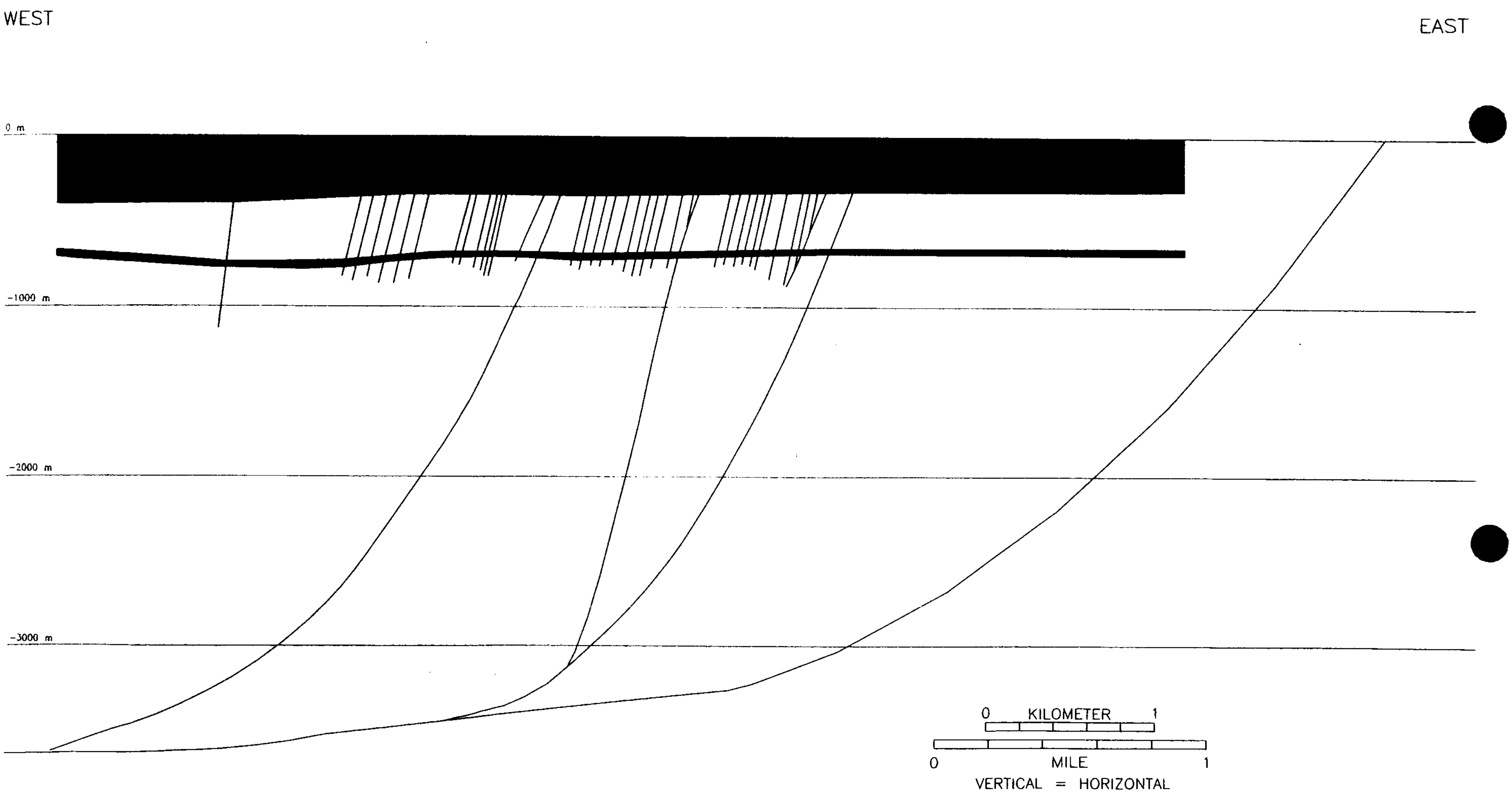
SECTION B–B': REVISED PRESENT–DAY INTERPRETATION (VERTICAL SHEAR MODEL)



38

FIGURE 15. Restoration of Fig. 14 to approximate top of the Topopah Spring Member. This model is well balanced. Vertical shear was used to model these faults because further work by Scott (1990) indicates that the small fault zones may be a complex anastomosing array, instead of discrete, planar surfaces.

SECTION B–B': TIVA CANYON MEMBER RESTORATION
(REVISED INTERPRETATION, VERTICAL SHEAR MODEL)



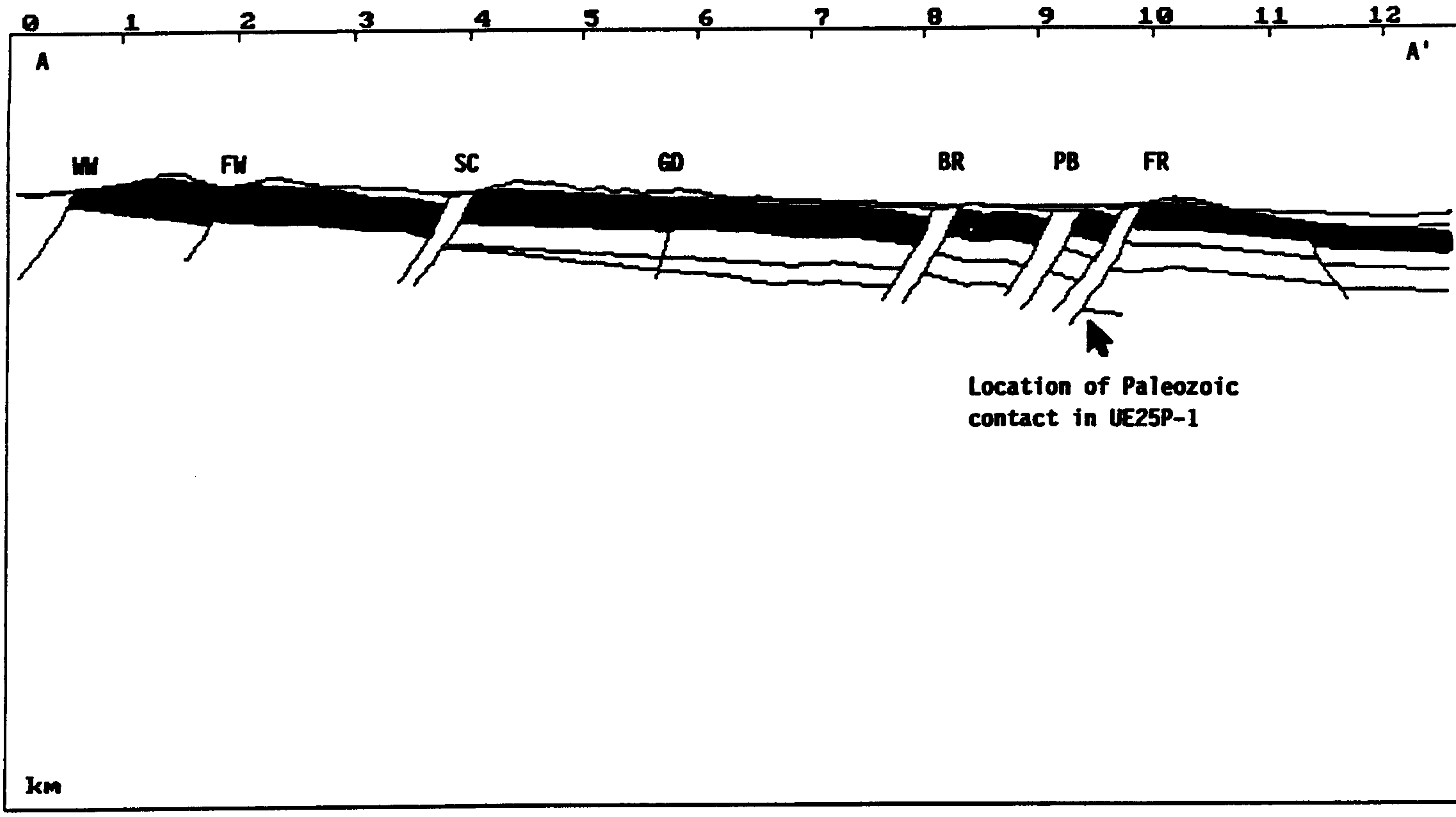


FIGURE 16. Digitized original version of section A - A' of Scott and Bonk (1984). Arrow shows location of contact of Tertiary volcanic rocks with the underlying Paleozoic section in the UE25P-1 bore hole (Carr et. al., 1986). Geologic unit highlighted in back is the Topopah Spring Member of the Paintbrush Tuff. FR = Fran Ridge fault; PB = Paintbrush Canyon fault; BR = Boundary Ridge fault; GD = Ghost Dance fault; SC = Solitario Canyon fault; FW = Fatigue Wash fault; WW -Windy Wash Fault.

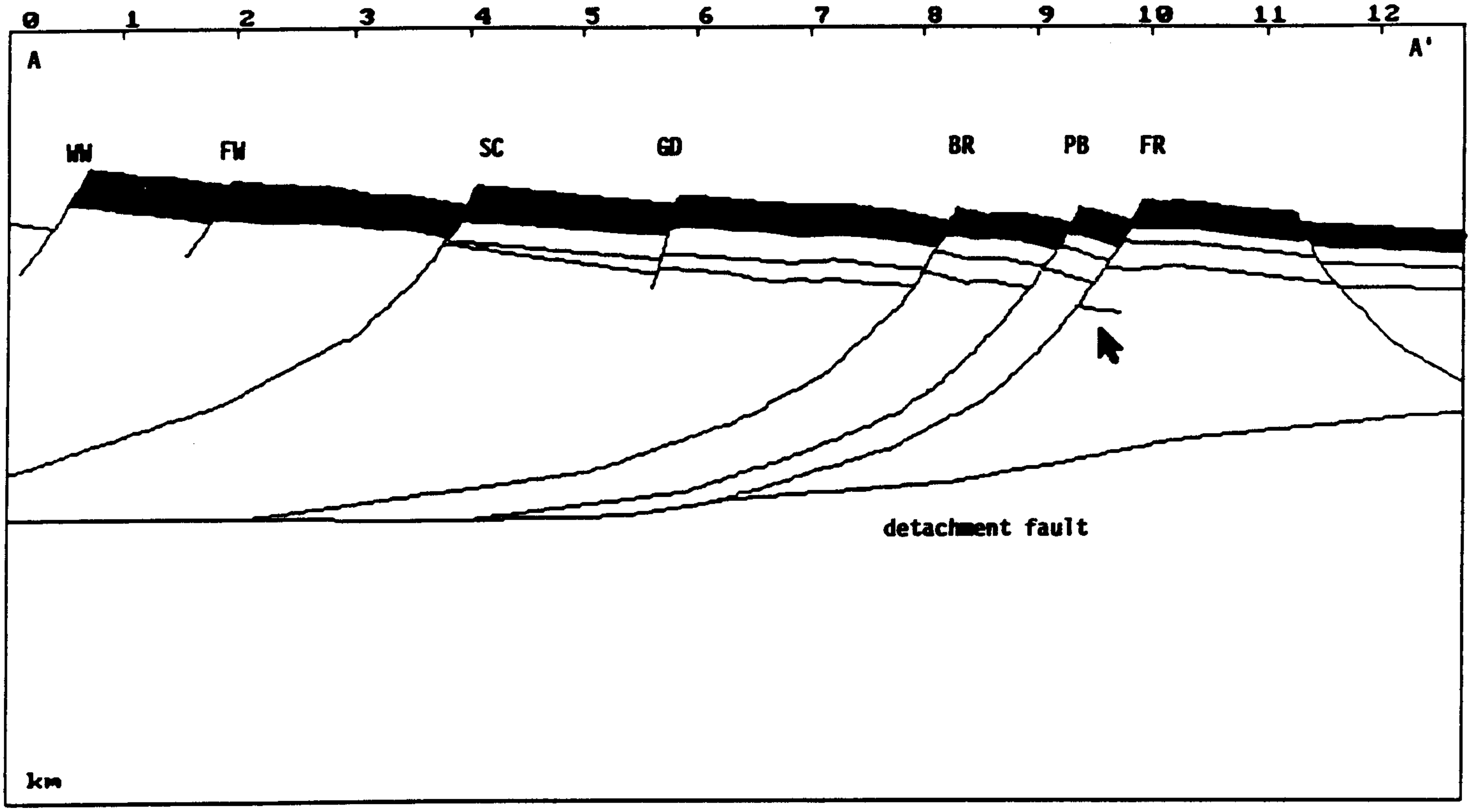


FIGURE 17. Balanced, linked-fault, low-angle detachment interpretation of section A - A' of Scott and Bonk (1984). Balanced fault trajectories were computed using vertical shear deformation for the Fran Ridge (FR), Paintbrush Canyon (PB), Boundary Ridge (BR) and Solitario Canyon (SC) faults. These faults were linked to a low-angle detachment constructed by computing depth to detachment for the overall system. The exact shape of the detachment is not known.

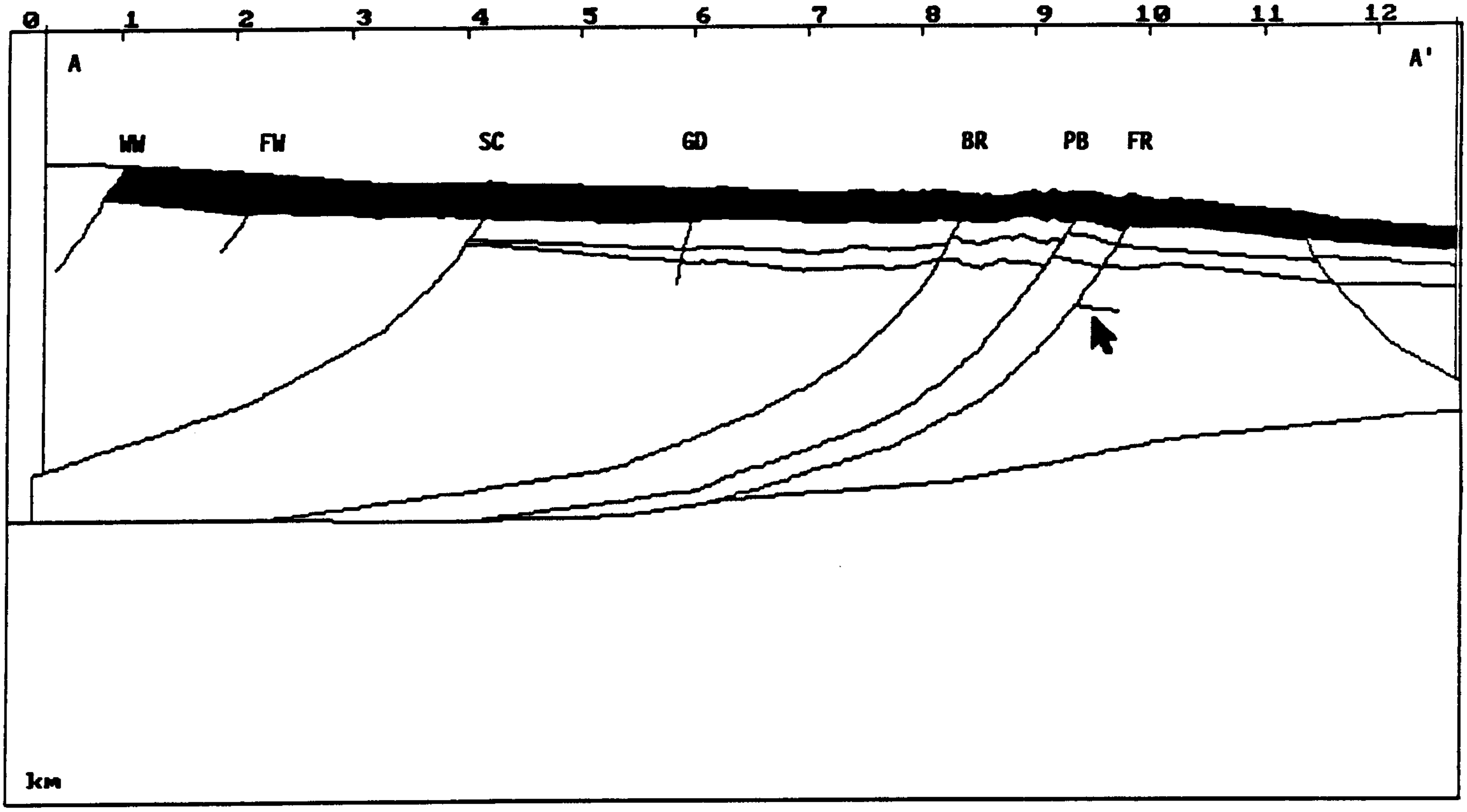


FIGURE 18. Restored state version of Fig. 17. Arrow shows location of Paleozoic contact in the UE25P-1. The restoration is by retrodeforming the section in vertical shear so that the top of the Paintbrush Canyon Member matches across the faults. This interpretation is fairly well balanced. There is some mismatch of horizons across the PB fault, but we believe the minor adjustments in the shape of the detachment below this area would fix this problem.

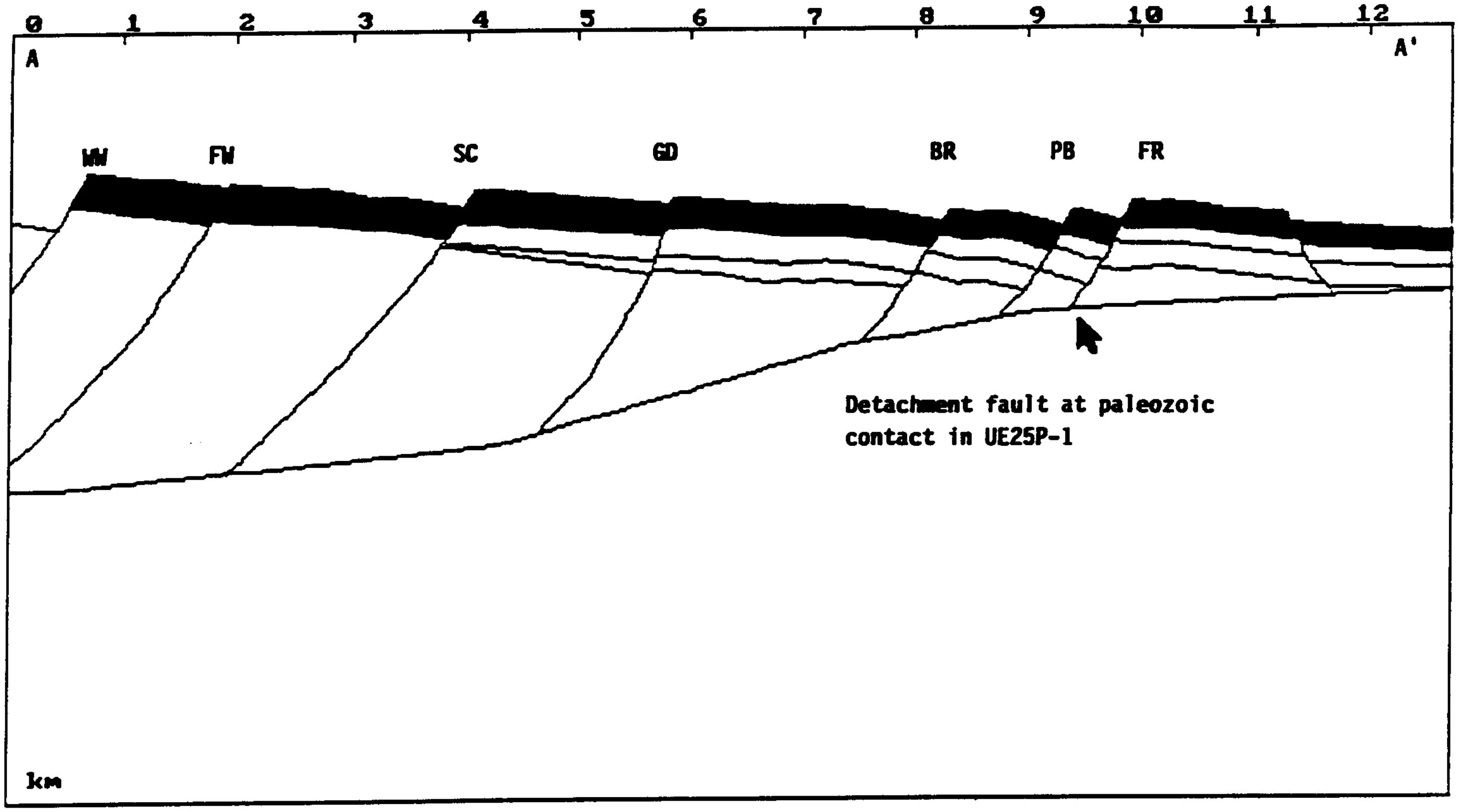


FIGURE 19. Low-angle detachment interpretation of section A - A' of Scott and Bonk (1984). This interpretation places the detachment at the contact between the Tertiary volcanics and the Paleozoic section. Small arrow shows location of contact in UE25P-1 bore hole.

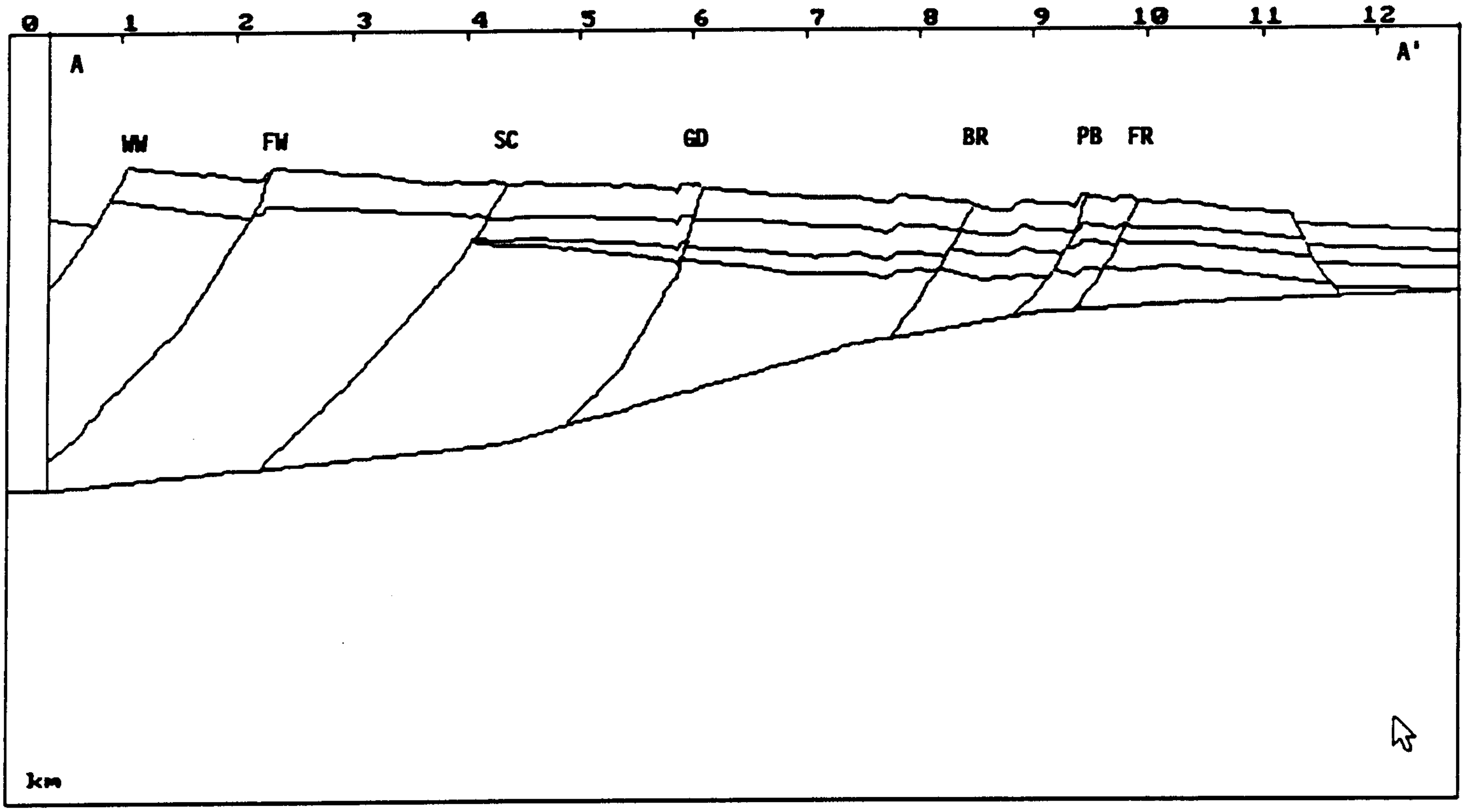


FIGURE 20. Vertical shear restoration of Fig. 19. The Topopah Spring is not colored in here so that the bedding mismatch and excess bed length can be seen. This section is not well balanced. Significant mismatch and excess bed length occur across the PB fault. The horizons match fairly well across the BR fault, but there is excess bedlength in the BR hanging wall. The Solitario restores well because the depth to detachment is deeper at that location, and more similar to the balanced interpretation in Fig. 18.

5. POTENTIAL FUTURE ACTIVITIES

Considering that an independent geological modeling effort would provide information to assist NRC technical staff in review of the work planned by the DOE for geological characterization of the site and site region and for assessment of site performance, there are several potential investigative activities related to the approach presented in this report which should be considered important enough to pursue in the future. These potential future activities, briefly outlined below, are categorized as short-term or long-term. The rationale addressing the need for each activity is also presented.

5.1 SHORT-TERM ACTIVITIES

(1) Balancing and analysis of Scott and Bonk (1984) cross sections A-A' and C-C' using the GeoSec software --- Results of this activity would provide additional information on subsurface fault geometry in the vicinity of Yucca Mountain, making it possible to determine if different structural concepts may be viable for different parts of Yucca Mountain.

(2) Continued investigation of simple shear deformation mechanisms in hanging wall blocks of major faults --- Use of antithetic shear surfaces as the simple shear internal deformation plane would provide additional analysis of the simple shear mechanism of deformation in the hanging wall blocks.

(3) Incorporation and analysis of existing seismic reflection data from lines run in the vicinity of Yucca Mountain --- This activity would provide additional information for control on the geometry of faulting at depth to assist in the analysis of faulting in the vicinity of Yucca Mountain.

5.2 LONG-TERM ACTIVITIES

(1) Comparison of strain accommodation mechanisms in hanging wall blocks of major faults --- This activity would address simple shear vs pure shear internal deformation mechanisms, and shed additional light on strain accommodation mechanisms in hanging wall blocks of faults.

(2) Incorporation and analysis of new seismic reflection data from lines run in the vicinity of Yucca Mountain --- New seismic lines would be digitized and analyzed as the data became available to assist in the analysis of faulting in the vicinity of Yucca Mountain and aid construction of regional tectonic models.

(3) Analysis of alternative geological models --- This iterative activity would be set up to specifically address construction of alternative models through the cross section balancing approach, progressing as more data became available. (Consideration of alternate concepts for the subsurface structure is seen from this

report to[illegible] a general part of this approach, so t[illegible]some of this is done in each case for analyzing a cross section.)

(4) Determination of a realistic geological framework, based on balanced cross sections, to include elements related to faulting, seismicity, volcanism, ground water flow, and radionuclide transport --- This "framework model", the determination of which would be iterative, would assist NRC staff in independently examining the geological framework models which will be proposed for Yucca Mountain for use in assessment of site performance. It would also assist with delineating gaps in the data base and with analyzing the validity of conclusions drawn concerning geometric and kinematic relationships of subsurface structures at Yucca Mountain. Early iterations for determining a realistic geological framework would assist NRC staff in the review of work planned by the DOE for geological characterization of the site and site region.

(5) Three-dimensional modeling --- This iterative activity would assist with the assembly of a three-dimensional geological framework model for Yucca Mountain and the surrounding area which would be used as a yardstick by NRC technical staff to assess three-dimensional models which will be proposed for Yucca Mountain and the surrounding region.

(6) Develop a framework for investigating fracture patterns theoretically developed in response to structural evolution of the Yucca Mountain area based on results from the balanced cross sections --- This activity would assist NRC staff with understanding stages of fracture development, and may be coupled to hydrologic studies and fracture mechanics by finite element analyses. Coupled modeling may include staged development of potential hydrologic flow pathways.

(7) Identify potential zones of weakness associated with fracture zones. These zones may be important to the assessment of natural resources and potential volcanic activity.

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7. GLOSSARY

(Unless indicated otherwise, all definitions are based on Bates and Jackson, 1987)

antithetic fault/antithetic shear plane - Fault/shear plane that is subsidiary to a major fault, formed in the same stress regime, oriented at a high angle to the major fault, and dips in a direction opposite to that of the major fault

detachment/detachment fault - a low-angle, basal main fault separating independent styles of deformation in the rocks above and below the detachment surface

dip reversal - "dip reversal" is synonymous with "rollover"

footwall/footwall block - the side of a fault underlying the fault surface/the block of rock on that underlying side ("footwall" is synonymous with "lower plate")

hanging wall/hanging wall block - the side of a fault overlying the fault surface/the block of rock on that overlying side ("hanging wall" is synonymous with "upper plate")

kinematic relationships - those relationships dealing with movements that took place within a rock mass during deformation, without any concern for linking those movements to stress history (Turner and Weiss, 1963)

listric fault - a curved, downward-flattening fault that is generally concave upward

pure shear - a type of irrotational strain (i.e. - strain in which the orientation of the principal strain axes remain unchanged) in which the mass being deformed is elongated in one direction and shortened at right angles to that direction

rollover - a feature of certain types of faults in which beds of the downthrown block dip toward the fault surface in an orientation opposite to that produced by drag (originally applied to Gulf Coast growth faults)

simple shear - a type of constant-volume, plane-strain deformation characterized by fixed orientation of one of the circular sections of the strain ellipsoid (deformation mechanism is closely approximated by the movements involved in shearing a deck of cards in one direction, since plane-strain deformation arises from displacements which are all parallel to a single plane)

synthetic fault/synthetic shear plane - fault/shear plane that is subsidiary to a major fault, formed in the same stress regime, oriented at a low angle to the major fault, and dips in the same direction as the major fault