USE OF BALANCED TWO-DIMENSIONAL GEOLOGICAL CROSS-SECTIONS IN DEVELOPMENT OF SCENARIOS FOR PERFORMANCE ASSESSMENT ANALYSES AT YUCCA MOUNTAIN, NEVADA

by

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ABSTRACT

Computerized cross-section balancing was applied to define a viable geologic framework for geometric representation of major faults beneath Yucca Mountain. The derived two-dimensional model consists of a linked listric-detachment fault system with the predicted detachment at a depth of 5.5 to 5.6 km below sea level. By considering the model in light of existing data, the following potential scenarios were formulated for consideration in preliminary assessment of site and repository performance: (1) Fault displacement scenarios involve distributive faulting on the linked fault system. Although the system may be decoupled from the present-day stress field, major northeast-trending faults are favorably oriented for oblique or strike slip. (2) Seismic hazard scenarios involve accommodating most seismogenic slip along structures deeper than the linked fault system, since the predicted detachment lies above the depth at which most earthquake foci are concentrated in this region. (3) Volcanic hazard scenarios

involve the linked fault system providing control on magmatic pathways from about 5.6 km below sea level to the surface.

INTRODUCTION

General Background

A balanced geological cross-section is one that can be geometrically restored (i.e. - retrodeformed) to its predeformed state by translation on mapped faults included in the section to remove effects of deformation without any resultant changes in cross-sectional areas in the plane of the section. It represents an interpretation of subsurface structures which, while non-unique, is both viable and admissible because it includes all observations on geometric relationships between faulting and related deformation. Hence, a balanced two-dimensional geological cross-section provides a more accurate picture of subsurface deformation than a cross-section which is not balanced.

Bally and others (1) published the first balanced geological cross-sections in their paper on analysis of thrust faulting in the Canadian Rockies, but Dahlstrom (2) was first to discuss mechanics of cross-section balancing in areas of thrust faulting. Because of these and other early efforts, wherein the method was extensively applied and proven in the petroleum industry, the approach has become standard for analyzing geometric and kinematic relationships of subsurface faulting in compressional terrains. Numerous authors have also addressed use of the method in extended terrains (3, 4, 5, 6, 7, 8, 9) and computerized techniques for balancing of cross-sections (9, 10). More recently, a computer-assisted cross-section

balancing approach has been specifically applied for geometric and kinematic analysis of subsurface faulting at Yucca Mountain (11).

Computer-assisted cross-section balancing provides a major convenience for handling the necessary manipulations more rapidly and with less chance for human error than the balancing-by-hand approach. The computer-assisted approach readily permits iterative balancing, so geological cross-section models can be modified and refined as additional data are acquired on geometry of faults and related deformation at Yucca Mountain. Computer-assisted construction and analysis of balanced cross-sections provides a powerful tool for developing and testing alternative tectonic framework models of the Yucca Mountain region, and rigorously assessing any alternative tectonic models and associated conclusions about geometric and kinematic relationships of subsurface structures which may be proposed.

Purpose and Objective

The purpose of this paper is to indicate how existing geologic information and computer-assisted techniques for geometric and kinematic analyses of subsurface structures can be used to assess the validity of geological cross-section models of the Yucca Mountain area, and to show how these methods assist in constructing a geological framework model (or models) for use in development of scenarios for performance assessment analyses. Discussion of geological concepts important for development of scenarios, rather than quantitative recommendations for incorporation of detailed geological information into performance assessment models, is the

focus of this paper.

Balanced geological cross-sections, carefully constructed to take into account field data and geometric relationships between fault shape and hanging wall block structures, are deemed fundamental for determining a viable subsurface geological framework for Yucca Mountain and the surrounding region. Assessment of the possibility of future repository disruption due to fault displacement, magmatic/volcanic activity and earthquake-induced seismicity will necessitate some level of scenario analysis in which a realistic geological framework is an important element. Computer-assisted cross-section balancing is used in this paper to develop an admissible subsurface geological framework for the region including Yucca Mountain. This geological framework represents, as realistically as possible, the subsurface geologic system of the region. It provides a geological foundation for development of potential scenarios to be used in performance assessment analyses. Discussion of the subsurface geological framework derived from balanced cross-sections and its importance in development of scenarios is the prime objective of this paper.

ANALYSIS OF YUCCA MOUNTAIN CROSS-SECTIONS

Assumptions and Constraints

Methods of geological cross-section balancing and analyses used in this study depend mainly on assumptions about undeformed-state geometries of geologic marker horizons, determination of marker cut-off positions in footwall blocks of faults, observations on orientations of bedding in hanging wall blocks, and

implementation of a simple shear mechanism for internal deformation in hanging wall blocks. The methods are generally limited to two-dimensional, plane-strain deformation models, so cross-sections oriented approximately in the direction of true dip of bedding should be used. Sections of this orientation are assumed to contain the principal slip direction. Therefore, the fault system is treated as a system initially generated by dip-slip movement. Conservation of cross-sectional areas with deformation is also an assumption of the approach.

A linked listric-detachment fault system is the fault model chosen for this study. A key assumption governing the selection of this fault model is based on field measurements of bedding dips observed in hanging wall blocks throughout the Yucca Mountain area. Bedding shows a relatively uniform eastward dip, with dip amount increasing in the hanging wall blocks with proximity to the surface trace of the underlying fault (12). This increase in dip of bedding toward a fault zone, termed "rollover" or "reverse dip", is considered to be diagnostic of deformation of bedding in hanging wall blocks lying above a listric fault system (3, 8, 13). Consequently, the presence of bedding rollovers in hanging wall blocks of faults at Yucca Mountain suggests the faults are listric at depth, and the interpretation of an underlying detachment fault into which they flatten and merge, or "sole", is geologically reasonable (14).

The concept of detachment faulting in the region of the Basin and Range surrounding Yucca Mountain is widely accepted by

geologists. Since Armstrong (15) first interpreted low-angle normal faults of areal extent in the eastern Great Basin of western Utah and eastern Nevada to be a consequence of major regional Tertiary extension, numerous workers have concentrated efforts on analysis of extensional deformation in this region. Based upon experience in the Basin and Range, Wernicke (16, 17) has proposed a regional model for low-angle detachment faulting in extensional terrains involving simple shear of continental lithosphere along shallow-dipping shear zones. Although some workers do not agree with certain details of the Wernicke model (16, 17), many have formulated regional concepts which incorporate aspects of this model for describing regional deformation of crustal rocks in Basin and Range extended terrain (18, 19). Maldonado (20) discussed extension of crustal rocks along a detachment fault system by listric and planar-rotational normal faults in the Bullfrog Hills of southern Nevada (Figure 1). The concept of detachment faulting in the region around and beneath Yucca Mountain was discussed by Hamilton (18), and Scott (21) has interpreted field data to indicate the presence of listric faults and detachment surfaces beneath Yucca Mountain. However, Carr (22) does not consider detachment faults to occur beneath Yucca Mountain based on interpretations involving a tectonovolcanic model for development of Crater Flat.

The relatively simple regional stratigraphy used in the analyzed cross-sections is probably simpler than that actually occurring at depth in the Yucca Mountain area because it is based

on information from relatively few, widely-spaced boreholes. Additional subsurface information will likely increase the complexity noted both within and between these stratigraphic units. More detailed stratigraphic information can be readily included in the cross-sections when it becomes available.

Data Sources

The index map of Yucca Mountain and the surrounding area shown in Figure 1 delineates the region upon which this study was focused. Two-dimensional geological cross-sections of Scott and Bonk (12) illustrating geometry and distribution of geologic structures at relatively shallow depth were the primary source of cross-section data used to constrain models of deep subsurface fault shape below Yucca Mountain. The entire suite of cross-sections from Scott and Bonk (12) were used as sources of data, including sections AA', BB', CC', DD', and EE' (Figure 2). Information from the geologic map of Scott and Bonk (12) which accompanied the cross-sections was used to further constrain the fault dips, fault locations, and topographic profiles shown in their published sections. Elevations of the top and bottom of the Topopah Spring Member of the Paintbrush Tuff (Unit Tptw) in Calico Hills and Little Skull and Skull Mountains (Figure 1) were obtained from Frizzell and Shulters (23) and Maldonado (24).

Appropriately oriented sections from Scott and Bonk (12) which were digitized directly and analyzed by cross-section balancing included combined section ABB' and sections BB' and CC' (Figure 2). Combined section ABB' was constructed to obtain a strike-normal

transect along the greatest length of section. Map data of Scott and Bonk (12) indicate the northwest end of section AA', from A to the intersection with section BB' at borehole USWH-5, is normal to strike of rock units and major faults and is, therefore, a true dip section. The entire length of cross-section BB' is normal to strike of the rock units and major faults. Consequently, the northwest end of cross-section AA' and all of BB' were combined to produce section ABB'.

The primary source of information for stratigraphic nomenclature and thickness of rock units was Scott and Bonk (12). Identification of certain units older than the Crater Flat Tuff was based on information in Carr and others (25). Figure 3 illustrates the stratigraphic units used in this study.

The western end of seismic reflection line AV-1 from Brocher and others (26), located in Figure 1 and illustrated in Figure 4, was used to interpret the approximate position of an inferred Fortymile Wash Fault. The aeromagnetic map of Glen and Ponce (27) also suggests a series of faults in the vicinity of Fortymile Wash by analogy with patterns shown for the Yucca Mountain block.

A series of shallow boreholes drilled in the vicinity of Yucca Mountain provided useful subsurface information on volcanic stratigraphy. The surface locations of these holes are shown in Figure 2. The deepest borehole used to constrain the published cross-section data, Borehole UE25P#1, reaches 1804 meters below the surface, or about 700 meters below sea level (25). Depths to Paleozoic rock below Yucca Mountain and Crater Flat were obtained

from seismic refraction data of Ackerman and others (28). Additional constraints on depth to Paleozoic rocks under Crater Flat were derived from the gravity model of Snyder and Carr (29).

Input Data

The following data drawn from the sources indicated above were critical for the cross-section balancing analyses. The geologic map and cross-sections of Scott and Bonk (12) were singularly important sources of information.

Elevation and geometry of undeformed-state "regional" marker horizon Tptw The top of the Topopah Spring Member of the Paintbrush Tuff (Unit Tptw of Figure 3) is exposed in the Calico Hills at an elevation of approximately 1190 meters (23). In Little Skull and Skull Mountains, the base of the unit is exposed at elevations of 1128-1450 meters (24). These exposures are the closest Tertiary volcanic rocks east of the area mapped by Scott and Bonk (12). Within the area mapped by Scott and Bonk (12), the highest elevation of the top of Tptw in the deformed hanging wall blocks is 1536 meters near the northwest end of their cross-section AA'. Hence, using a thickness of 330 meters for Tptw based on data from Scott and Bonk (12), the constraints on elevation of the top of Tptw east of Fortymile Wash are 1780 meters maximum and 1536 meters minimum. This elevation range is interpreted to represent the pre-deformational "regional" level of the top of the unit. In the absence of evidence for major thickness changes in the Paintbrush Tuff and contiguous stratigraphic units, it is further assumed that Tptw was deposited horizontally within relatively

narrow limits. Consequently, it is deemed reasonable to use the top of Tptw as a "regional" marker horizon for restoring balanced cross sections to their undeformed states, with the undeformed marker horizon lying at an elevation between 1536 and 1780 meters.

Deformed-state hanging wall block geometry Although the top of Tptw is not exposed everywhere, its near-surface geometry can be constrained by measurements of bedding orientation from overlying stratigraphic units based on field data of Scott and Bonk (12) and by borehole data. Consequently, data exist for constructing the present-day geometry and position of the top of Tptw, and this unit can be used as a deformation marker horizon with a relatively high degree of confidence to represent the deformed-state hanging wall block geometry. Because its subsurface position must be inferred from well data and projections from other stratigraphic horizons for some hanging wall blocks, however, geometry of all hanging wall blocks is not precisely known and there is a range of permissible interpretations for deformed geometry of Tptw in hanging wall blocks.

Deformation mechanisms Simple shear along vertical or oblique (synthetic or antithetic) shear planes is considered a viable mechanism for internal deformation in hanging wall fault blocks in extensional terrains (3, 7, 8, 14, 30). Vertical simple shear has been used to represent the deformation mechanism in hanging wall blocks for kinematic and geometric analysis of faulting at Yucca Mountain (11). Field evidence from Scott and Bonk (12) and Scott (21) suggests that a simple shear mechanism is reasonable for

internal deformation of hanging wall blocks in the Yucca Mountain area. At several locations, Scott and Bonk (12) showed in their cross-sections and on the accompanying map numerous, small-displacement, normal (synthetic) faults lying close to major faults. In a later publication, Scott (21) reinterpreted these small faults as an anastomosing system of small fractures which could be averaged as approximately vertical. For this study, these structures were interpreted as evidence, as Scott (21) did, that the hanging wall blocks deformed internally along near-vertical shear planes that were not parallel to bedding. Consequently, field evidence strongly supports the choice of vertical shear as the preferred deformation mechanism.

Initial modelling of fault trajectories was conducted using shear plane orientations varying from 70 degrees synthetic to 60 degrees antithetic. This relatively narrow range of orientations for the deformation mechanism shear planes was predicated upon existence of the high-angle, small-displacement normal faults as described by Scott and Bonk (12) and Scott (21). Because field evidence is strong for the vertical shear deformation mechanism, a possible alternative mechanism for internal deformation of hanging wall blocks above listric normal faults which invokes bedding-parallel flexural slip (31, 32) was not analyzed in detail in this study. However, preliminary analyses for comparison purposes using a bedding-parallel flexural slip deformation mechanism indicated this mechanism gave results similar to those for the vertical shear mechanism for fault trajectories (i.e. - fault shape at depth) and

depth to detachment.

Initial fault dip Measured dips of major faults in the Yucca Mountain area vary between 54 and 82 degrees west, and cluster strongly in the 60-75 degree west range in bedrock (12). Faults included for analysis in this study, from east to west across Yucca Mountain, are the inferred Fortymile Wash, Paintbrush Canyon, assumed Midway Valley, Bow Ridge, and Solitario Canyon Faults (Figure 2). The only fault with a dip constrained by subsurface data is the Paintbrush Canyon Fault. Borehole UE25P#1 intersects Paleozoic rocks at a faulted boundary, interpreted to be the Paintbrush Canyon Fault, at a depth of 1244 meters from the surface (25). This information gives a dip of approximately 66 degrees west when the surface trace of the fault as shown by Scott and Bonk (12) is taken into account. Therefore, for this study, the initial dip of major faults being modeled is considered to be 66 degrees west.

Dipping detachment surface A gently-dipping detachment surface with the dip direction parallel to the general direction of transport of the upper plate is consistent with existing models of regional tectonic development in extensional terrains (17, 18, 19, 21). Applying this concept for regional geometry of the detachment surface, a gently westward-dipping detachment was used in this study.

Approach and Results

The method used in this study to predict fault trajectory and depth to detachment and construct balanced cross-sections is the

same as that previously applied at Yucca Mountain by Young and others (11). The mechanics of the method, initially developed by Verrall (14), are discussed in detail in Young and others (11). Yucca Mountain is well-suited to this approach because surface and shallow subsurface geologic controls are good, whereas very little direct information, and only sparse geophysical data, are available for depths greater than 2 km.

Heaves and throws for the five faults analyzed were determined as follows by measurement in combined section ABB' of Scott and Bonk (12), using an assumed dip of 66 degrees west for the faults and the top of Tptw as the offset marker: the inferred Fortymile Wash Fault (throw, t = vertical component of net slip = 1030m; heave, h = horizontal component of separation or displacement = 457m); Paintbrush Canyon Fault (t = 424m, h = 197m); an assumed Midway Valley Fault (t = 99m, h = 43m); Bow Ridge Fault (t = 105m, h = 46m); Solitario Canyon Fault (t = 200m, h = 85m). Consequently, these faults have sufficiently large displacements to be considered as major structures.

<u>Determination of fault trajectories and depth to detachment fault surface</u> Iterative fault prediction analyses were conducted to generate balanced subsurface fault trajectories for all five major faults being studied. Iterations involved initial modelling of fault trajectories using shear plane orientations varying from 70 degrees synthetic to 60 degrees antithetic to determine the sensitivity of fault trajectory results to orientation of the shear plane. The factors deemed critical in computation of the fault

trajectories were as follows:

1. Choice of undeformed-state "regional" marker horizon.
2. Choice of deformed-state hanging wall block geometry.
3. Choice of deformation mechanism(s).
4. Choice of initial (near-surface) fault dips.
5. Inference of the Fortymile Wash Fault.

Inference of the Fortymile Wash Fault was a key step which allowed the entire fault array model of Yucca Mountain to be balanced. Dips in units east of the Bow Ridge Fault could not be restored to an undeformed state relative to the undeformed marker horizon without the presence of a fault in the vicinity of Fortymile Wash, an inference that was also made in the study of Yucca Mountain by Young and others (11).

When several faults are assumed to flatten and merge into a single detachment surface as this study has done, it is necessary to apply certain constraints for fault trajectory prediction to satisfy this geometric relationship. These constraints may be expressed as follows:

(a) Area created between marker horizon and deformed hanging wall = Area leaving section = Heave x Depth to detachment;

(b) Vertical drop of hanging wall geometry over planar section of fault / Heave = tangent of angle of dip of detachment.

Using the notation shown in Figure 5, the following conditions must be satisfied to accommodate these two constraints:

(1) A(1) / H(1) = A(2) / H(2) = ... A(n) / H(n) = D

(2) V(1) / H(1) = V(2) / H(2) = ... V(n) / H(n) = tan(alpha)

where A(n) = area between the marker horizon and hanging wall as a result of motion on fault n; V(n) = vertical drop of hanging wall geometry over the planar section of fault n; H(n) = heave of fault n; D = vertical depth to detachment below any deformed hanging wall segment above the planar portion of the fault surface; and alpha = dip angle of detachment fault.

In practice, these constraints are taken into account by modifying the hanging wall block geometry of each of the faults until the two conditions expressed above are met. Because these modifications must not violate geological controls provided by field and borehole data, there is a limitation to modifications which can be made. For this study, it was discovered thorough iterative analysis of the cross-sections that the higher marker horizon elevation (i.e. - 1780 meters) created a minimum depth to detachment for the Fortymile Wash Fault which was considerably deeper than could be matched by any permissible modifications to geometry of other faults in the sections. Therefore, to obtain convergence of all fault trajectories at a single detachment surface, it was necessary to select an elevation for the marker horizon less than the maximum. Moreover, to preserve a gentle westerly dip on the detachment surface as dictated by regional interpretations (17, 18, 19, 21), the elevation could not be decreased below about 1600 meters, because of Condition 2 above, if other faults in the sections were to have heaves and vertical hanging wall drops consistent with a gently westward-dipping, rather than a horizontal, detachment surface. An elevation of 1656

meters for the marker horizon permitted all faults to merge into a single detachment surface having a regional dip of 8 degrees west.

For determining fault trajectories and depth to detachment, the major faults were considered to have developed sequentially from east to west. Each fault developed its deformed hanging wall block geometry by deformation of the pre-existing regional marker horizon which lay in the deformed hanging wall block of the adjacent fault to the east (Figure 6). Each marker/hanging wall block/fault segment "set" could then be used to determine a discrete fault trajectory for each major fault to analyze depth to detachment. This east to west-breaking sequence of fault development is simply a matter of convenience for the cross-section balancing, and the same finite deformed state is achieved whether the faults develop by breaking from east to west or west to east. It was noted, however, that slip along the inferred Fortymile Wash Fault was great enough to cause immediate deformation of the repository block once displacement on that fault was included in the fault model.

Young and others (11), using the same techniques as this study, suggested the geometric need for a fault in the vicinity of Fortymile Wash and predicted a resultant detachment level at 2.3 km below sea level. In the current study, interpretation of geometry related to the Fortymile Wash Fault has been refined, and the estimate of pre-deformational level of the top of regional marker horizon Tptw modified, to result in prediction of a deeper detachment surface at 5.5 to 5.6 km below sea level. Predicted

depth to the detachment surface is the principal difference between results from the current study and those from Young and others (11).

Construction of balanced cross-sections The conditions to be satisfied for balancing of cross-sections were that the faults should be consistent with geometry of the observed hanging wall block deformation (or with reasonably assumed geometry, taking into account field and borehole information for hanging wall blocks where deformation could not be observed because the marker horizon was not detectable), and linked at depth to a single detachment surface.

Figures 7 through 9 show the revised, balanced, present-day deformed state interpretations of sections ABB', BB', and CC'. Figure 10 illustrates restored section ABB' to indicate that the section, as interpreted, can be retrodeformed to its unstrained state by translation on the faults included in the section without any changes in cross-sectional areas within the section that would lead to a gross mismatch of the marker horizon across the fault surfaces. Therefore, the assumptions applied for this study produce a series of well-balanced cross-sections that illustrate a viable and admissible interpretation of subsurface structures in the vicinity of Yucca Mountain.

Fortymile Wash Fault The interpretation that a listric normal fault exists near Fortymile Wash is based on several factors. First, the elevation of the top of Tptw in borehole J-13 (Figure 2) is approximately 800 meters above sea level, whereas in Calico

Hills (23) and Little Skull and Skull Mountains (24), the projected elevation of the top of the unit is between 1780 and 1190 meters. This is a change in elevation of 300-980 meters for an across-strike distance of 2 km in the Calico Hills, and 8 km for Little Skull and Skull Mountains. Second, dips in bedding at Fran Ridge and Alice Point vary between 4 and 20 degrees east and average about 10 degrees east (12). These dips imply the existence of a normal fault east of Fran Ridge. Third, the western end of seismic reflection line AV-1 of Brocher and others (26) intersects the trend of Fortymile Wash at its southern extension. Preliminary examination of those data makes it possible to interpret a down-to-the-west fault with normal displacement in the vicinity of Fortymile Wash (Figure 4). Fourth, aeromagnetic data shown by Glen and Ponce (27) suggest faulting in and adjacent to Fortymile Wash (i.e. - east of Fran Ridge and including Fortymile Wash). Preliminary examination of the aeromagnetic patterns at that locale are similar to those over known faults in the Yucca Mountain block, where the faults tend to lie adjacent to elongate, northeast-trending magnetic lows.

Ghost Dance Fault Based on existing sparse data, the exact nature of the Ghost Dance Fault is uncertain at this time. Several possibilities exist for explaining the character of the Ghost Dance. One possibility is that it may be one of the simple shear planes proposed as the internal deformation mechanism of the hanging wall block for the Bow Ridge Fault. Another is that it may be an incipient, major, hanging wall block bounding fault; or it

may connect with the Abandoned Wash Fault to the south, as shown on maps presented by Scott (21) and Coppersmith and Youngs (33), to form a structure that is comparable to other major faults at Yucca Mountain. However, Scott and Bonk (12) mapped no bedding rollovers associated with the Ghost Dance Fault, and it was not treated as a major structure in this study. Interpretation of the Ghost Dance as a major fault was not required for balancing the sections. Additional data on the Ghost Dance can be readily incorporated into the balanced cross-section analyses as the data become available.

CONCLUSIONS ON POTENTIAL IMPORTANCE FOR SCENARIO DEVELOPMENT

Balanced geological cross-sections provide a means of developing a regional geological framework model (or models) for Yucca Mountain and the surrounding area which represents a geometrically reasonable interpretation of subsurface structures. While a balanced geological cross-section does not define a unique solution for subsurface geometry of faulting and related deformation, development of geological framework models and consideration of scenarios in light of balanced cross-sections assures that a viable geometric and kinematic model representing admissible interpretations of subsurface structures will be used in performance assessment analyses. Therefore, use of balanced geological cross-sections for development of realistic subsurface geological framework models and realistic scenarios is considered important at Yucca Mountain to determine potential effects of components of the natural system on site and repository performance.

The concepts presented result from interpretations based on analysis of balanced geological cross-sections derived from a linked listric-detachment fault system model for Yucca Mountain and the surrounding area. Other models can be analyzed in the future to investigate alternative tectonic models. Considering at this time only the described listric-detachment fault model, several factors which should be considered in construction of realistic scenarios for performance assessment analyses at Yucca Mountain have been derived. These factors are summarized below as geological concepts important for consideration in development of scenarios, rather than as quantitative recommendations for incorporation of detailed geological information into performance assessment models. The exact manner in which these factors should be quantitatively included in scenarios for performance assessment analyses will require additional thought to assure that appropriate geological data are properly translated into model parameters.

Implications for Representation of Fault Geometry

Listric faults and detachment geometry A model involving listric faults which flatten and merge into a single detachment surface is a reasonable geometric interpretation for major faults occurring in the repository area. Field evidence of rollover geometry in the exposed hanging wall blocks of the major faults is strong evidence that the proposed linked listric-detachment system evolved mainly as a dip-slip fault system (12, 21), and the fact that sections balanced suggests they have responded mainly in a dip-slip deformation mode.

The amount of extension related to development of the proposed linked fault system suggested by this study is 7-10 percent within the Yucca Mountain block, an amount which is in agreement with the 10 percent estimate of Scott (21) for the northern part of Yucca Mountain. This amount of "local" extension of the Yucca Mountain block is grossly different from that required for extension of the region around Yucca Mountain, which has been estimated by Maldonado (20) at greater than 100 percent, and up to 275 percent locally, for the Bullfrog Hills area (Figure 1) northeast of Yucca Mountain.

Depth to detachment The single detachment into which these faults sole, based on the balanced sections used in this modeling effort, lies at a depth of 5.5 to 5.6 km below sea level. Even with the existing concept that several detachment surfaces may occur in the region around and beneath Yucca Mountain (21), the balanced geometry of the suite of faults analyzed in this study suggests they can all be linked to a single detachment surface at the depth indicated.

Inferred Fortymile Wash Fault Inference of this fault indicates a listric normal fault, not previously defined, which is equivalent to other major faults at Yucca Mountain. Amount of slip modeled along the Fortymile Wash Fault, based on displacement of the fault as indicated by calculated values for heave and throw, caused deformation of the hanging wall block containing the potential repository at Yucca Mountain. Seismic (26) and aeromagnetic (27) evidence has been used in this study to suggest a series of faults in the vicinity of Fortymile Wash similar to those which bound the

Yucca Mountain block, all of which are part of a linked listric-detachment fault system. Scott (21) reports there is no evidence of a fault cutting Quaternary deposits in Fortymile Wash. However, sections would not balance using the proposed linked listric-detachment model without a fault in the vicinity of the Fortymile Wash.

Ghost Dance Fault The Ghost Dance Fault lies between the Solitario Canyon and Bow Ridge Faults and cuts into the repository block. Because of sparse data, it is not possible to make definitive interpretations about the character of the Ghost Dance Fault from this study. Consequently, little can be said about its potential importance in scenario development at this time.

Implications for a planar fault model A planar fault model seems less geometrically reasonable for the fault system at Yucca Mountain based on field evidence of rollover geometries in hanging wall blocks of some major faults (12, 21). Axen (34) clearly indicates that planar faults require consistent dips for deformed bedding, rather than dips which steepen towards the fault surface. For future consideration of alternative tectonic models, planar fault models will be analyzed.

Implications for Fault Displacement Hazard

Distributive faulting Considering the linked nature of the listric-detachment fault system suggested by this study, distributive faulting and associated deformation along the fault system is a conceivable scenario. That is, if slip did occur, it could occur on more than one strand of this linked fault system.

Hence, fault displacement concerns exist, even if seismicity is not a concern, for the fault system at Yucca Mountain. The concept of distributive faulting has been espoused for the Yucca Mountain area by Ramelli and others (35).

Implications for future slip under current stress field Patton and Zandt (36) infer the current state of stress in the southern Great Basin to be maximum (horizontal) compressive stress oriented northeast-southwest and minimum (horizontal) compressive stress oriented northwest-southeast. These orientations agree with the N65W orientation for minimum horizontal principal stress determined at Yucca Mountain from hydraulic fracturing by Stock and others (37), and with the N50W to N70W orientation for minimum (subhorizontal) principal stress suggested by Rogers and others (38) from evaluation of seismicity in the southern Great Basin.

The present stress field is different from that indicated at Yucca Mountain for development of the major normal faults analyzed in this study. Fault-slip lineations on normal and strike-slip faults measured by Scott and Hofland (39) suggest a minimum horizontal compressive stress oriented nearly east-west (N89E to N85W). Considering the current state of stress indicated by Patton and Zandt (36), Stock and others (37) and Rogers and others (38), it is conceivable that parts of the fault system could experience oblique slip or strike slip in the future. Rogers and others (38) speculate that Yucca Mountain may be decoupled from the current stress field by underlying detachment faults, but did not preclude the possibility of slip on the linked listric-detachment system or

on faults beneath that system. Scott (21) has identified sinistral, oblique to horizontal-slip, northeast-trending faults in the central and southern parts of Yucca Mountain. The largest of these faults, the Stagecoach Road, shows 5-7 m of left-lateral (sinistral) offset (40). Scott (21) indicates that this fault may connect with the Paintbrush Canyon Fault to the northeast. The likelihood of fault displacement on this linked fault system and the possible magnitude of displacements were not assessed.

Potential importance of the Bare Mountain Fault Location and dip of the Bare Mountain Fault, an east-dipping structure bounding Bare Mountain on the east (Figure 1), has been defined by Reheis (41). Additional constraints on location and dip of the Bare Mountain Fault can be derived from interpretation of the gravity model of Snyder and Carr (29). This fault is conceptually interpreted by Scott (21) as a major structure that cross-cuts the shallow detachment surface to which the listric faults analyzed in this study are geometrically linked. That is, the Bare Mountain Fault, of known Quaternary age (41, 42), has been interpreted as a deeper-seated structure extending below the modeled detachment surface. While Hamilton (17) considers the Bare Mountain Fault to be an eastward-tilted detachment, if interpretation of the fault as a deeper-seated structure is correct, future displacement along the listric-detachment fault system may be limited because it has been deactivated by the cross-cutting Bare Mountain Fault. In this case, the Bare Mountain Fault could be the structure nearest to Yucca Mountain for accommodating future major displacement.

Implications for Seismic Hazard

Thickness of seismogenic crust in the western United States is approximately 15-20 km (36, 43). Therefore, the detachment surface predicted in this study clearly lies within the present-day seismogenic crust.

Sibson (43) provides data for the region including California and part of the southern Great Basin which indicate most microearthquakes occurred in the upper 10 to 12 km of the crust, and shocks greater than magnitude 5.5 originated mainly at depths of 10 to 12 km. Based on information from historical seismicity in the southern Great Basin, Rogers and others (38) indicate that the greatest number of earthquakes are confined to the upper 15 km of crust. However, foci cluster at a depth around 8 km for the region including the Nevada Test Site, with a distinct minimum number of events at 4 km depth (38). Regionally in the southern Great Basin, Rogers and others (38) indicate a bimodal depth distribution at about 1.5-2 km and 7-8 km depth. While Patton and Zandt (36) show depths around 5 km for earthquake foci of three events in southwestern Nevada, Vetter and Ryall (44) determine a mean depth for strike-slip events at about 7 km, with oblique and normal slip events at mean depths around 12 km and 13 km, respectively, for western Nevada. Patton and Zandt (36) do not recognize the change in mechanism with focal depth suggested by Vetter and Ryall (44). Doser (45) presents information on 13 historical earthquakes of the Basin and Range of magnitude 6 or greater nucleating near the base of the brittle-ductile transition zone. Rogers and others (38)

point out low seismicity levels at Yucca Mountain and conclude that Yucca Mountain may be decoupled from the regional stress field because of one or more underlying detachment surfaces, but do not eliminate the possibility of seismic slip on the listric-detachment system or on faults beneath the system.

Vetter and Ryall (44) further interpret the data to indicate that fault plane dips decrease about 25 degrees from the surface to around 15 km depth, suggesting major near-planar faults may become listric near this depth. In contrast to this interpretation, Doser (45) interprets data on historical earthquakes of the Basin and Range to indicate earthquakes occurred on faults dipping 38 degrees or greater, with no evidence for listric or low-angle planar faulting. Rogers and others (38) infer normal or strike-slip mechanisms, and report that no subhorizontal focal mechanisms are shown in the southern Great Basin or at Yucca Mountain. Doser (45) indicates that about 38 percent of the faulting was normal, and 46 percent strike-slip in the Basin and Range region, while Patton and Zandt (36) indicate that strike-slip faulting predominates in southern Nevada.

Although different interpretations exist, there is an implication that the listric-detachment fault system modeled at Yucca Mountain, with a depth to detachment around 5.5 to 5.6km below sea level, lies above the depth at which most earthquake foci are concentrated. Therefore, seismic risk may be a lesser concern for the linked fault system than for deeper-seated structures. As discussed above, aseismic fault displacement on the linked listric-

detachment fault system is not precluded.

Implications for Volcanic Hazard

If the listric-detachment fault model is correct, the implications for volcanic hazard involve possible shallow control on location of dikes and vents by northeast-trending faults, but no deep-seated control on pathways by these faults. Based on results from this study, this control could have extended no deeper than about 5.6 km below sea level. Different structures would provide conduits from deeper-seated magmatic sources to levels in the crust where the northeast-trending fault system could control extrusion of igneous materials at the surface. The northeast alignment of basaltic cones in Crater Flat, pointed out by Crowe (46) and Smith and others (47), suggest that these structures have, in the past, exercised control on location of surface vents.

SUMMARY OF KEY IMPLICATIONS FOR SCENARIO DEVELOPMENT

Scenarios developed for assessment of site and repository performance should be built around a geologic framework which represents geological structures beneath Yucca Mountain as realistically as possible. This study indicates a linked listric-detachment fault system model is viable and admissible at Yucca Mountain since it can be used to construct balanced geological cross sections. Field evidence of bedding rollovers in hanging wall blocks of major faults at Yucca Mountain strongly supports the linked listric-detachment fault geometry interpretation. However, because balanced cross-section solutions are non-unique, construction and testing of alternative tectonic models (e.g. - a

planar fault model or a multiple detachment model) are not precluded by results of this study. Potential key implications for subsurface geological framework and scenario development derived from analysis of balanced cross-sections using the linked fault model are as follows:

(1) Fault geometry representation - A linked listric-detachment fault system model, with depth to detachment around 5.5 to 5.6 km below sea level, is proposed for representation of subsurface fault geometry at Yucca Mountain. A newly-inferred listric normal fault in the vicinity of Fortymile Wash is interpreted to be a part of this linked fault system, which includes, from east to west, the inferred Fortymile Wash, Paintbrush Canyon, assumed Midway Valley, Bow Ridge, and Solitario Canyon Faults. Conclusions about the Ghost Dance Fault are not drawn because data are too sparse to include it in the modeling, but sections did balance without inclusion of the Ghost Dance as a major listric fault. Planar fault geometry for the major faults at Yucca Mountain are contraindicated because of the strong field evidence for listric faulting from bedding rollovers in hanging wall blocks of major faults.

(2) Fault displacement hazard - Possible scenarios for fault displacement involve distributive faulting on the linked listric-detachment fault system. Although the linked system is interpreted to be the result of mainly dip-slip movement, northeast-trending faults in this system are favorably oriented to experience oblique or strike-slip movement under the present stress field. The linked

listric-detachment fault system may be decoupled from the present stress field and from major fault displacement, possibly by the Bare Mountain Fault if it cross-cuts the predicted detachment surface.

(3) Seismic hazard - Although the linked listric-detachment fault system, with a predicted detachment surface around 5.5 to 5.6 km below sea level, lies within the seismogenic crust, the fault system appears to lie above the depth where most earthquake foci are concentrated in this region. Also, the linked fault system may be decoupled from the present stress field and, consequently, decoupled from seismogenic slip. Therefore, possible scenarios for seismic hazard involve accommodating most of the seismic slip along deeper-seated structures.

(4) Volcanic hazard - Possible scenarios for volcanic hazard involve northeast-trending faults of the linked listric-detachment fault system providing control on magmatic pathways from about 5.6 km below sea level to the surface. In this case, the linked fault system would strongly influence surface locations of vents, cones, and fissures in the Yucca Mountain area. Deeper-seated structures would be required for tapping magmatic sources at their origin and feeding magma to the linked fault system.

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The paper is an independent product of the CNWRA and does not necessarily reflect the views or the regulatory position of the NRC. Cross-sections presented herein were constructed and analyzed using GEOSEC (Version 2.0) software, a product of CogniSeis Development, Inc., of Houston, Texas.

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REVISED FIGURE CAPTIONS FOR PAPER BY STIREWALT, YOUNG AND MORRIS ENTITLED "USE OF BALANCED TWO-DIMENSIONAL GEOLOGICAL CROSS-SECTIONS IN DEVELOPMENT OF SCENARIOS FOR PERFORMANCE ASSESSMENT ANALYSES AT YUCCA MOUNTAIN, NEVADA" ----- Revised 27 May 1992 -gls-

Figure 1. Index map of Yucca Mountain and surrounding area. Named faults include FMD = Funeral Mountains Detachment Fault; BHD = Bullfrog Hills Detachment Fault; FC = Fluorspar Canyon Fault; BM = Bare Mountain Fault; CH = Calico Hills Fault; PR = Point of Rocks Fault; RM = Red Mountain Fault. Teeth occur on upper plates of identified low-angle normal faults; fault traces are dotted where concealed, and marked by queries where uncertain. AV-1 = location of seismic line AV-1 of Brocher and others (26). LW = Lathrop Wells basaltic volcanic center. Asterisks in Crater Flat mark locations of basaltic vents. (Modified after Scott (21), Figure 14.)

Figure 2. Detailed map of Yucca Mountain showing locations of boreholes and cross sections AA′, BB′, CC′, DD′, and EE′ of Scott and Bonk (12). From east to west, named faults include PCF/FRF/SRF = Paintbrush Canyon Fault/Fran Ridge Fault/Stagecoach Road Fault; MVF = assumed Midway Valley Fault: BRF = Bow Ridge Fault; GDF/AWF = Ghost Dance Fault/Abandoned Wash Fault; SCF = Solitario Canyon Fault; FWF = Fatigue Wash Fault; WWF = Windy Wash Fault. (Fault locations from Scott (21), Figure 3 and Coppersmith and Youngs (33), Figure 1.)

Figure 3. Stratigraphic column for balanced cross sections. Note position of the Topopah Spring Member of the Paintbrush Tuff (Tptw), the regional marker horizon used in this study.

Figure 4. Western end of seismic line AV-1 at intersection of the southern extension of Fortymile Wash between Stations 889 and 1249, showing features interpreted in this study as normal faulting in the vicinity of Fortymile Wash. (Unmigrated 0-5s stack from Vibroseis source in relative amplitude format after Brocher and others (26), Figure 28a.)

Figure 5. Geometric constraints on hanging wall block geometry for merging balanced listric fault trajectories into a single detachment surface. Upper figure shows constraints for fault F(1); lower figure, for fault F(2). Boxed information summarizes the conditions which must be satisfied for multiple listric faults to sole into a single detachment.

Figure 6. Respective positions of the top of regional marker horizon Tptw used to determine subsurface fault trajectories and depth to detachment when slip is modeled along major faults breaking sequentially from east to west across Yucca Mountain. From east to west, the following faults are included: inferred Fortymile Wash, Paintbrush Canyon, assumed Midway Valley, Bow Ridge, and Solitario Canyon Faults. This figure is based on combined cross-section ABB′.

Figure 7. Revised, balanced, present-day (deformed-state) cross section ABB′. From east to west, the following major faults sole into the detachment: inferred Fortymile Wash, Paintbrush Canyon, assumed Midway Valley, Bow Ridge, and Solitario Canyon Faults. Predicted detachment surface lies around -5.6 km below sea level. For stratigraphy shown in the section, refer to stratigraphic column of Figure 3.

Figure 8. Revised, balanced, present-day (deformed-state) cross section BB′. From east to west, the following major faults sole into the detachment: inferred Fortymile Wash, Paintbrush Canyon, assumed Midway Valley, and Bow Ridge Faults. The Solitario Canyon Fault is not included because original section BB′ from Scott and Bonk (12) does not extend to this fault. Predicted detachment surface lies around -5.2 km below sea level. For stratigraphy shown in the section, refer to stratigraphic column of Figure 3.

Figure 9. Revised, balanced, present-day (deformed-state) cross section CC′. From east to west, the following major faults sole into the detachment: inferred Fortymile Wash, Fran Ridge-Paintbrush Canyon, and Bow Ridge Faults. An assumed Midway Valley Fault is not included because original cross-section CC′ from Scott and Bonk (12) does not show this fault. Predicted detachment surface lies around -5.5 km below sea level. For stratigraphy shown in the section, refer to stratigraphic column of Figure 3.

Figure 10. Geometrically restored (retrodeformed) cross-section ABB′ illustrating good match of stratigraphic units across major fault surfaces after slip has been removed. From east to west, the following major faults are shown: inferred Fortymile Wash, Paintbrush Canyon, assumed Midway Valley, Bow Ridge, and Solitario Canyon Faults. For stratigraphy shown in the section, refer to stratigraphic column of Figure 3.

FIG. 1

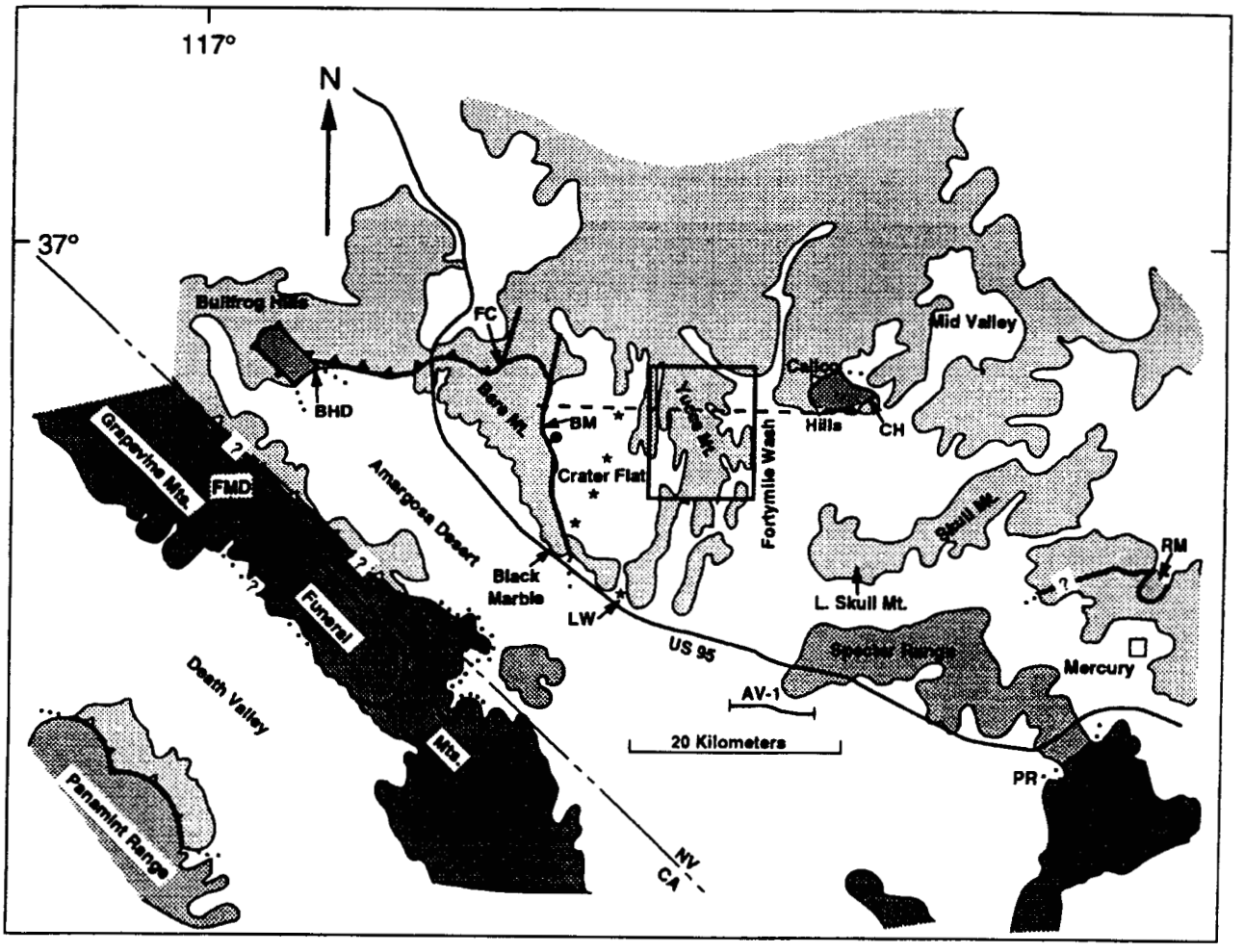

117°
N
37°
Bullfrog Hills
FC
BHD
Bare Mt.
BM
Crater Flat
Yucca Mt.
Fortymile Wash
Mid Valley
Calico
Hills
CH
Grapevine Mts.
FMD
Amargosa Desert
Black
Marble
LW
Skull Mt.
L. Skull Mt.
RM
Funeral
Mts.
Death Valley
US 95
Specter Range
Mercury
AV-1
20 Kilometers
PR
Panamint Range
NV
CA

FIG. 2

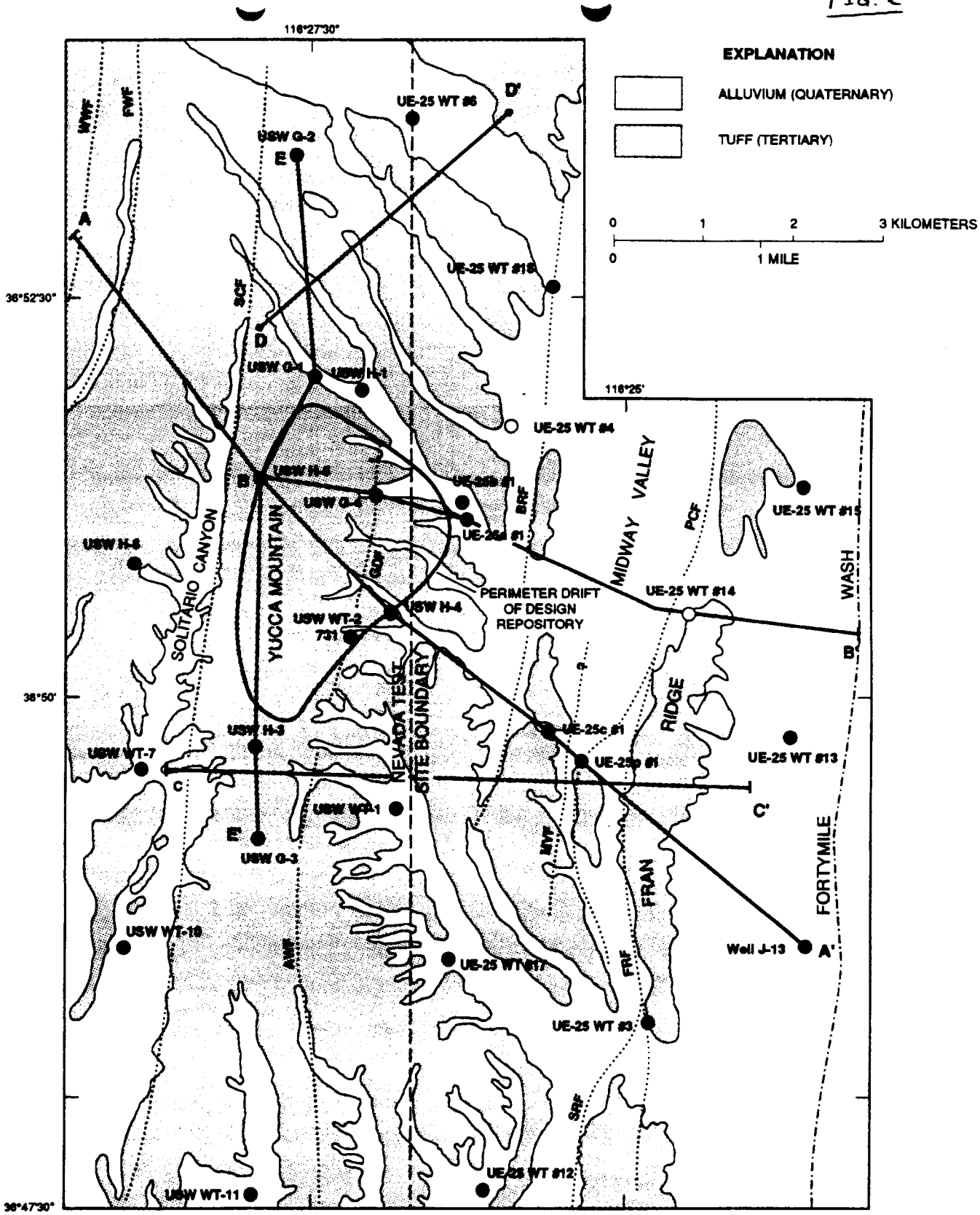

EXPLANATION
ALLUVIUM (QUATERNARY)
TUFF (TERTIARY)
0 1 2 3 KILOMETERS
0 1 MILE
116°27'30"
116°25'
36°52'30"
36°50'
36°47'30"
UE-25 WT #6
D'
USW G-2
E
A
UE-25 WT #16
D
USW G-1
USW H-1
UE-25 WT #4
B
USW H-6
USW G-4
UE-25b #1
UE-25a #1
UE-25 WT #15
USW H-6
SOLITARIO CANYON
YUCCA MOUNTAIN
MIDWAY VALLEY
PERIMETER DRIFT OF DESIGN REPOSITORY
UE-25 WT #14
USW WT-2
731
USW H-4
WASH
B'
NEVADA TEST SITE BOUNDARY
RIDGE
UE-25c #1
UE-25p #1
UE-25 WT #13
USW H-5
USW WT-7
C
C'
USW WC-1
E'
USW G-3
FRAN
FORTYMILE
USW WT-10
Well J-13
A'
UE-25 WT #17
UE-25 WT #3
UE-25 WT #12
USW WT-11

FIG. 3

STRATIGRAPHIC COLUMN FOR SECTIONS

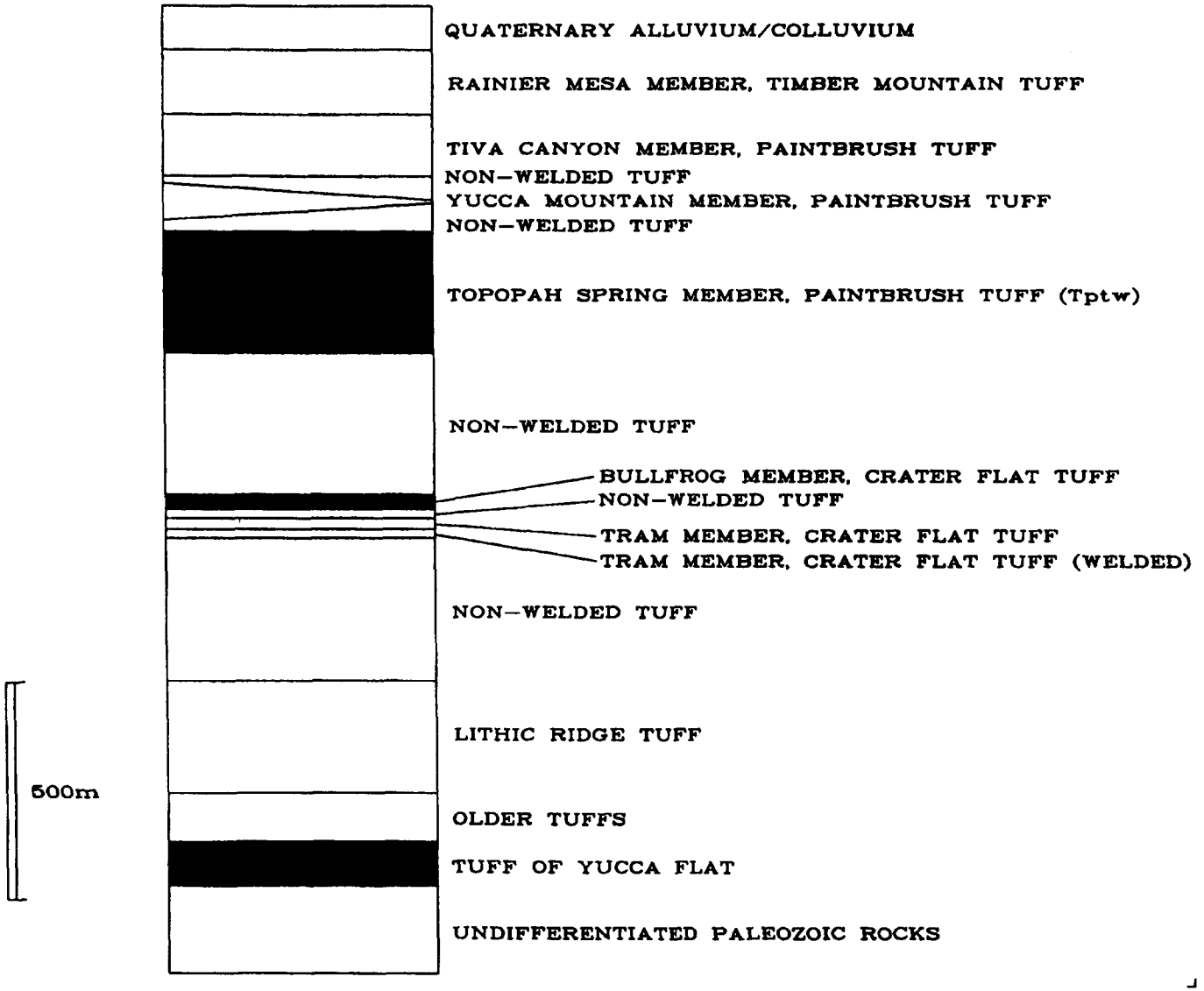


FIG. 4

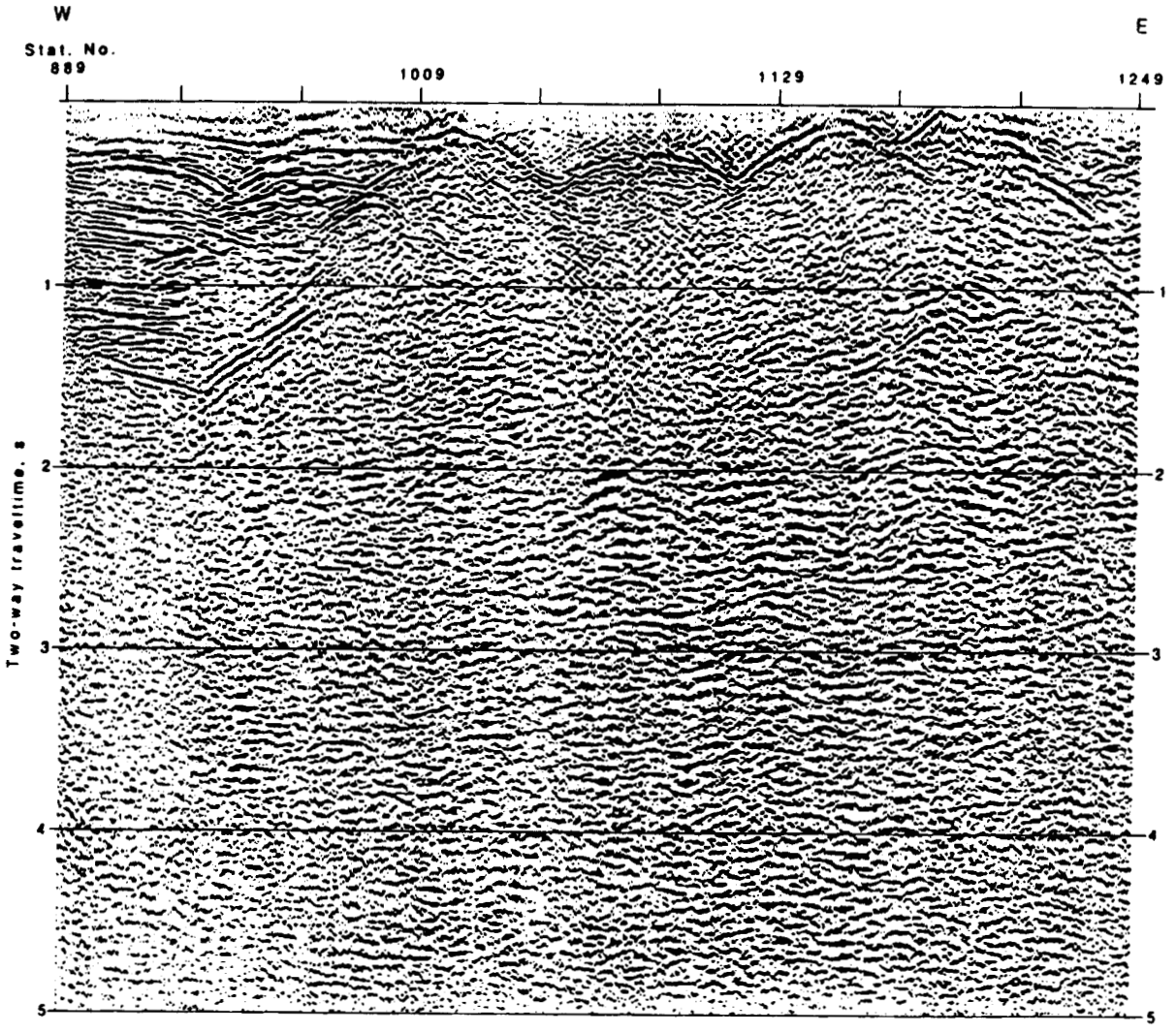
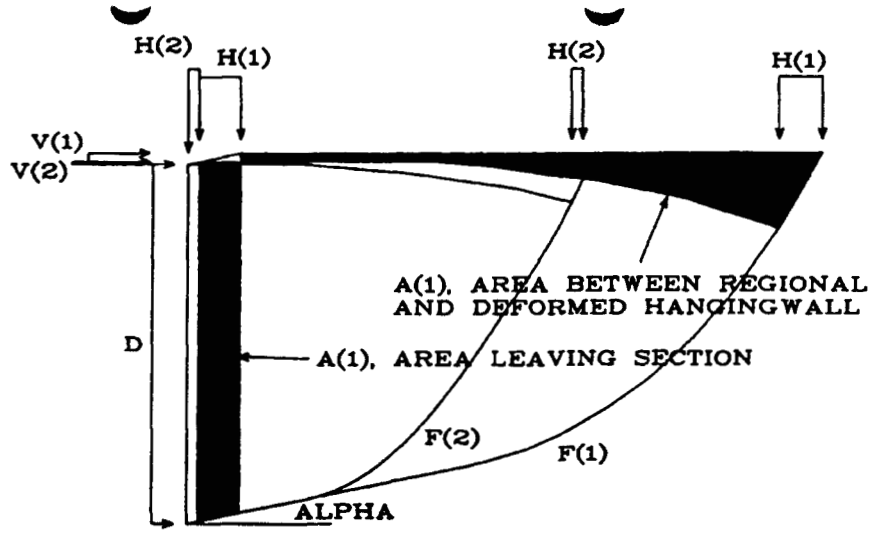
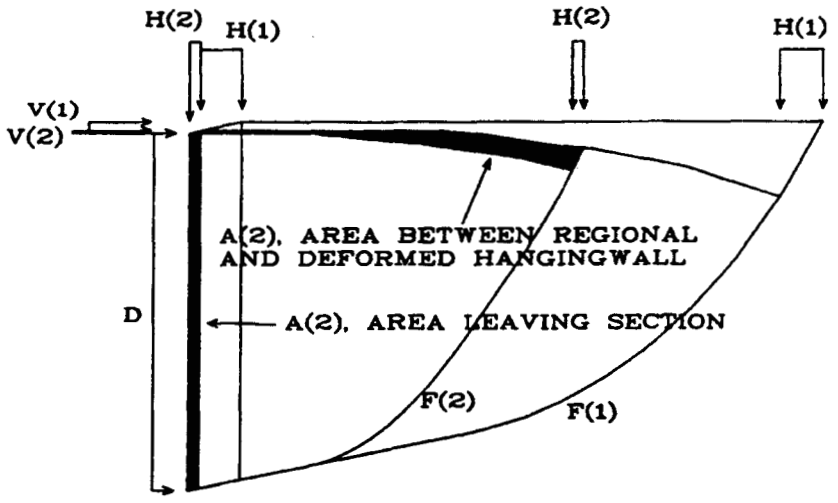


FIG. 5



V(1)/H(1) = V(2)/H(2) = TAN (ALPHA)

A(1) = H(1).D



V(1)/H(1) = V(2)/H(2) = TAN (ALPHA)

A(2) = H(2).D

FOR COINCIDENCE OF DETACHMENTS, SET:

V(1)/H(1) = V(2)/H(2) = ... V(n)/H(n)

AND:

A(1)/H(1) = A(2)/H(2) = ... A(n)/H(n)

FIG. 6

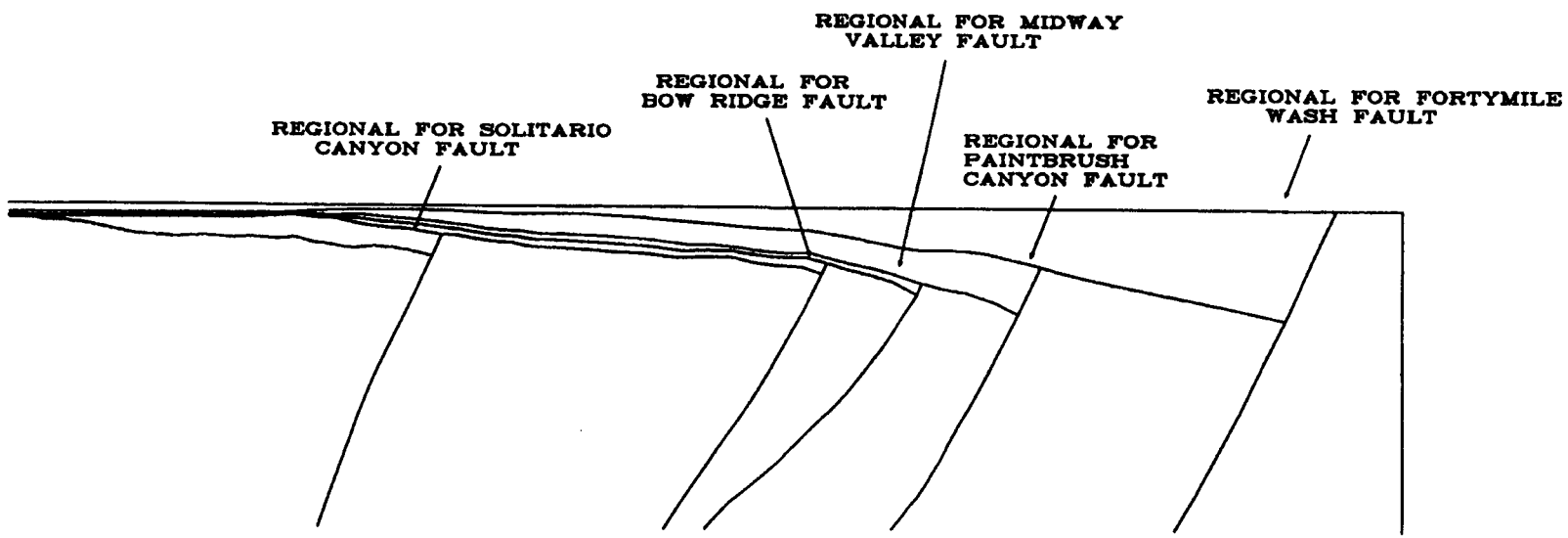

REGIONAL FOR MIDWAY VALLEY FAULT
REGIONAL FOR BOW RIDGE FAULT
REGIONAL FOR FORTYMILE WASH FAULT
REGIONAL FOR SOLITARIO CANYON FAULT
REGIONAL FOR PAINTBRUSH CANYON FAULT

FIG. 7

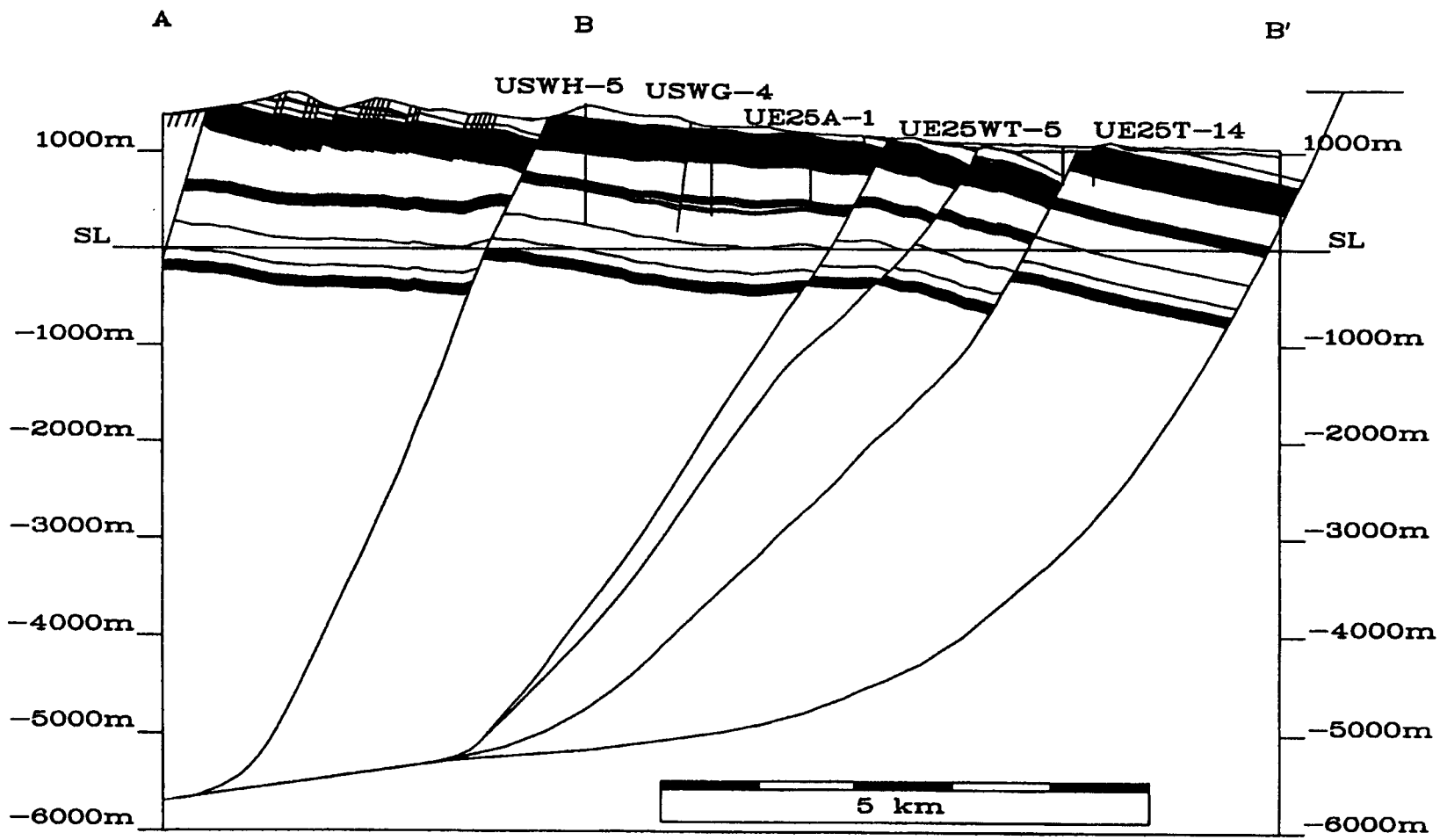

A
B
B'
USWH-5
USWG-4
UE25A-1
UE25WT-5
UE25T-14
1000m
SL
-1000m
-2000m
-3000m
-4000m
-5000m
-6000m
5 km

FIG. 8

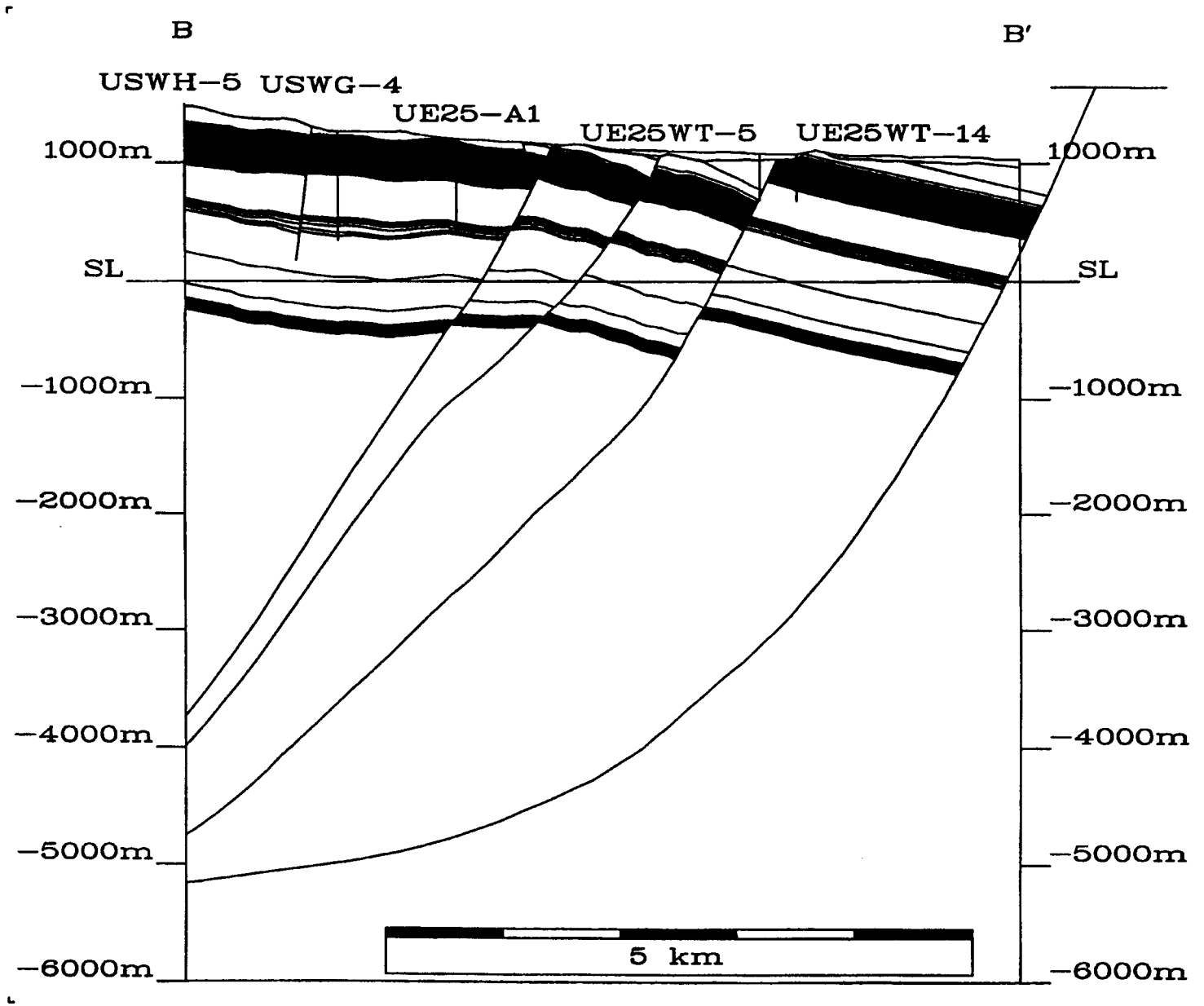

B
B'
USWH-5
USWG-4
UE25-A1
UE25WT-5
UE25WT-14
1000m
SL
-1000m
-2000m
-3000m
-4000m
-5000m
-6000m
5 km

FIG. 9

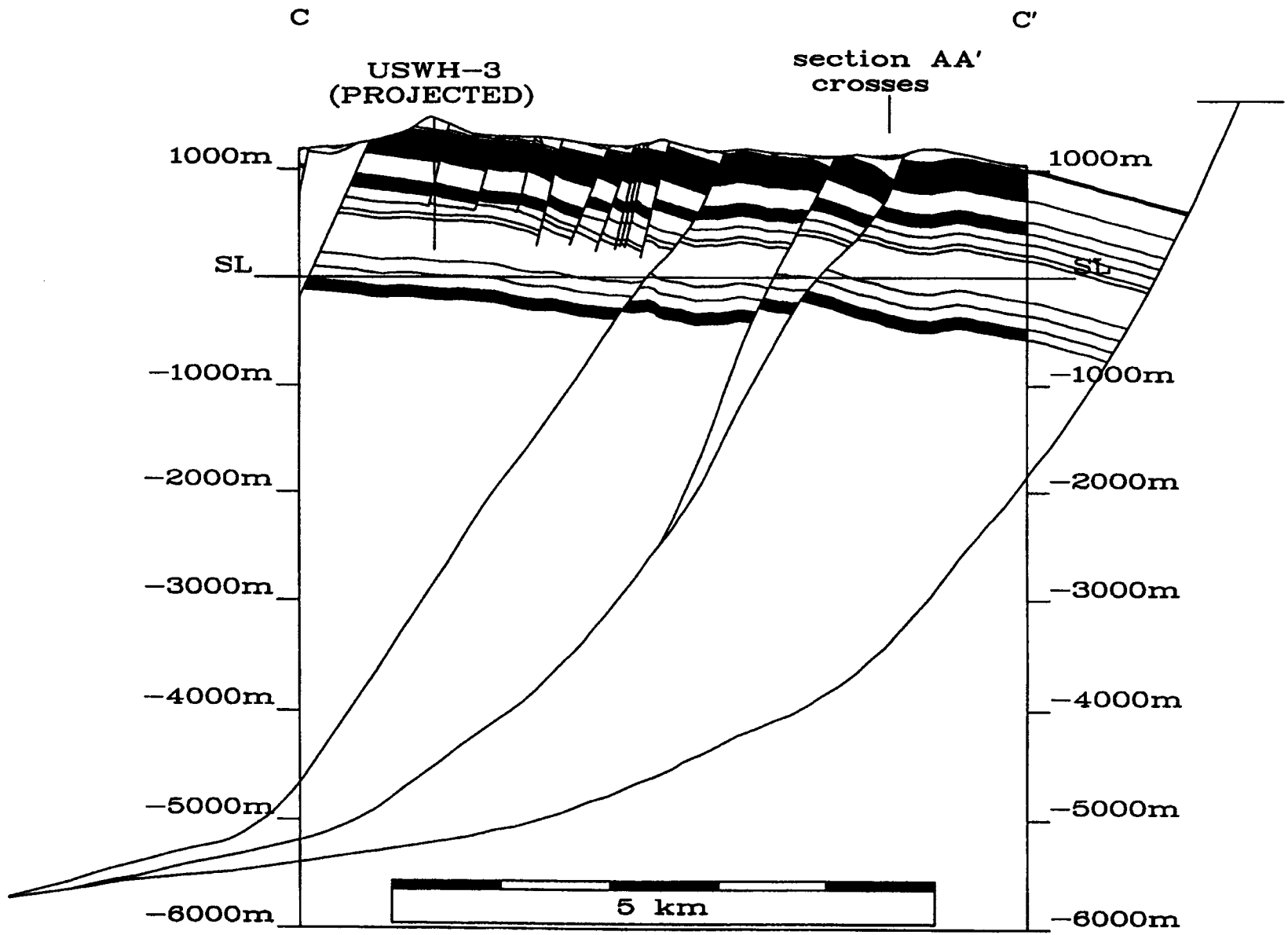
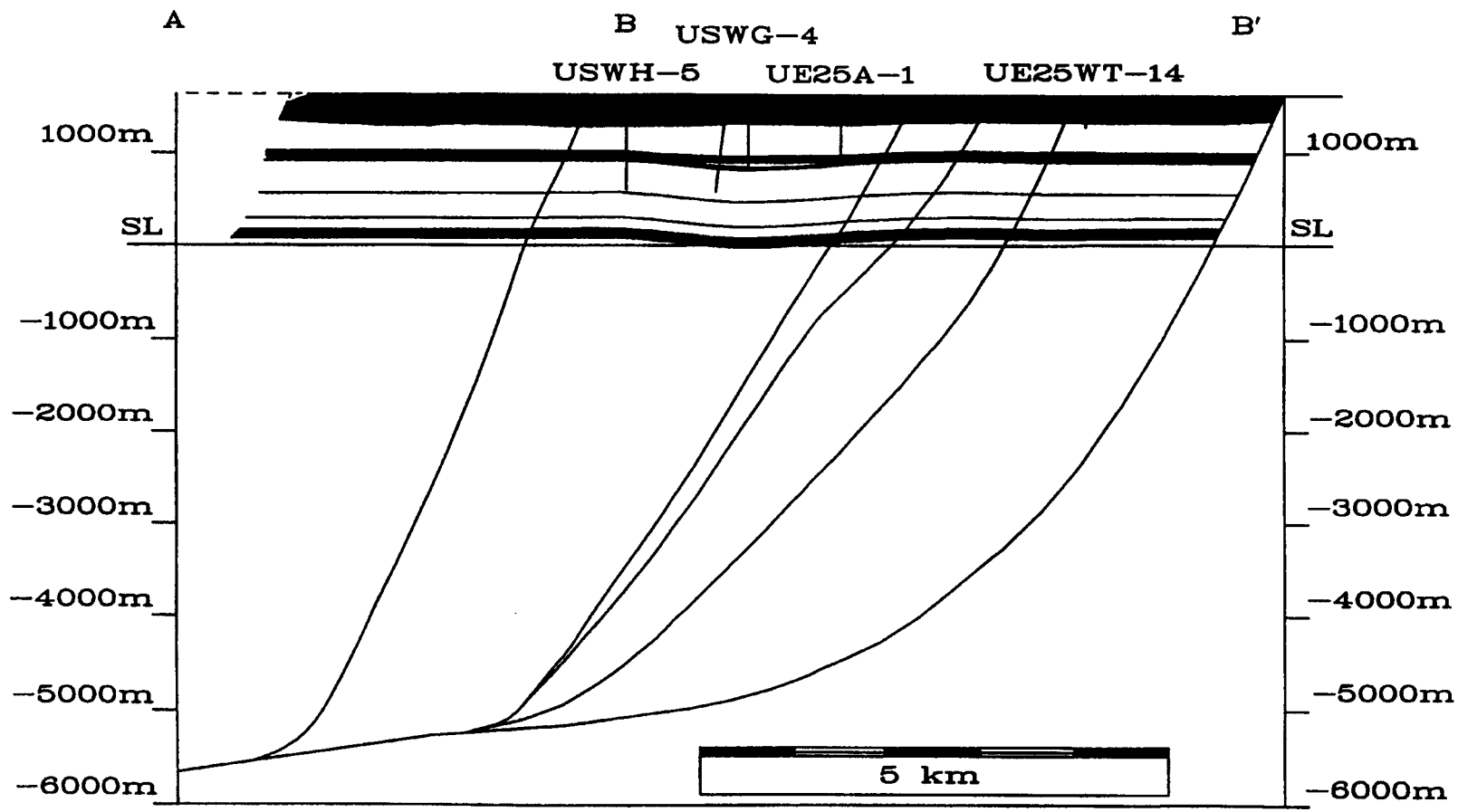

C
C'
USWH-3
(PROJECTED)
section AA'
crosses
1000m
SL
-1000m
-2000m
-3000m
-4000m
-5000m
-6000m
1000m
SL
-1000m
-2000m
-3000m
-4000m
-5000m
-6000m
5 km

FIG. 10


A
B
USWG-4
B'
USWH-5
UE25A-1
UE25WT-14
1000m
SL
-1000m
-2000m
-3000m
-4000m
-5000m
-6000m
1000m
SL
-1000m
-2000m
-3000m
-4000m
-5000m
-6000m
5 km