CNWRA 92-024

PRELIMINARY STRUCTURAL INTERPRETATION OF SEISMIC REFLECTION LINE AV-1

Prepared for

Nuclear Regulatory Commission
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Stephen R. Young
Alan P. Morris
Gerry L. Stirewalt

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ABSTRACT

Preliminary structural geologic interpretations of the AV-1 seismic reflection line have been produced to: (i) determine implications of the AV-1 reflection seismic data for development and assessment of cross section structural models of Yucca Mountain and (ii) to support U.S. Nuclear Regulatory Commission (NRC) assessment of uncertainties associated with the use of reflection seismic data to detect and investigate subsurface geologic features in the vicinity of Yucca Mountain. Compatibility of modeled and interpreted fault trajectories suggests that simple shear is a valid approximation of the overall hangingwall deformation mechanism for the tectonically extended terrain in the Yucca Mountain-Amargosa Desert region. Preliminary geologic interpretation of AV-1 supports the presence of a major basin-bounding structure on trend with the east flank of the Fortymile Wash-Jackass Flats valley. This structure can be interpreted from the seismic data as a major, relatively discrete, west-dipping normal fault. However, forward modeling of the entire fault system interpreted from the seismic data suggests that the structure may be more complex. Forward modeling of a multi-level detachment interpretation indicates that a hangingwall syncline should form above a ramp connecting the two detachment levels. This type of structure explains key aspects of the basin-bounding structure shown on the west end of the AV-1 record section. This is a fundamentally new alternative conceptual model of extensional deformation in the vicinity of Fortymile Wash. The structural style suggested by interpretation and geometric models of faulting on AV-1 is consistent with that determined for Yucca Mountain. The AV-1 data strongly suggest that the major basin-bounding faults imaged on the record section merge into a low-angle detachment fault system within an estimated depth range of 5 to 6 km below sea level (about 6-7 km below ground surface). Both modeled and interpreted depth to detachment estimates are in good agreement with detachment depths estimated at Yucca Mountain. However, an alternative interpretation and model of the AV-1 data suggests that a multiple-detachment model should also be examined as a possible paradigm for faulting at Yucca Mountain. Significant difficulties encountered in interpreting the AV-1 amplitude record section are lack of good quality data below about 1-1.5 seconds of two-way travel time (twtt) and insufficient resolution of available velocity data. Large-scale structures (>0.5-1 km wide) on the amplitude record can be reliably interpreted and modeled in the range of 1-1.5 s twtt (1-2 km). With the processing currently available, finer-scale geologic features are not reliably resolved in the amplitude record. Substantial improvement in resolution may be possible by reprocessing the field data using interactive velocity analysis methods, and by using combined methods of interactive geometric modeling and synthetic imaging of resultant geologic models.

CONTENTS

FIGURES

ACKNOWLEDGMENTS

Section restoration, fault trajectory modeling and time-depth/depth-time conversions were performed using GEOSEC(tm), a product of CogniSeis Development Inc., Houston, Texas.

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-88-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards (NMSS), Division of High-Level Waste Management (DHLWM). The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

1 INTRODUCTION

Geological interpretation of reflection seismic data often yields new information and insight critical to effective investigation and assessment of subsurface geological features. Resource exploration and development routinely includes acquisition of reflection seismic data. Integrated scientific investigations of the nature of Earth's crust and upper mantle and studies of crustal-scale tectonics and geodynamics have come to depend heavily on deep reflection profiling (e.g., COCORP; McCarthy and Thompson, 1988). As part of the ongoing and planned site characterization activities at Yucca Mountain, Nevada, the U.S. Department of Energy (DOE) intends to acquire reflection seismic data at Yucca Mountain (Oliver et al., 1990). The use of reflection seismic surveys, in conjunction with exploratory boreholes, is a generally effective approach to detecting buried geologic features, particularly faults, and to determining geometry and extent of fault surfaces. It is anticipated that the DOE will utilize reflection seismic data to some extent for direct detection and characterization of subsurface geologic features related to both favorable and potentially adverse conditions. Furthermore, these data may be used to support development of regional tectonic and structural geologic models of Yucca Mountain.

The NRC may need to review and evaluate geological interpretations of seismic data used by the DOE to investigate faulting processes and to develop tectonic models of Yucca Mountain. Because of the geological complexity and ground surface conditions at Yucca Mountain, use of reflection seismic techniques to determine the occurrence of subsurface geologic features is considered to be a Key Technical Uncertainty in the Compliance Determination Strategy (CDS) on structural deformation [10 CFR 60.122(c)(11)]. The primary concern here is the effectiveness of the reflection method for resolving buried faults. Use of alternative tectonic models to assess hazards related to earthquake seismicity and igneous activity is also considered to be a Key Technical Uncertainty. The DOE is specifically required to adequately investigate potentially adverse conditions, including the extent to which the condition may be present and still be undetected taking into account the degree of resolution achieved by the investigations [10 CFR 60.122(a)(2)(i)]. Accordingly, preliminary structural geologic interpretations of existing AV-1 reflection seismic data are produced. The purpose of this work is to (i) determine the implications of geologic interpretations of the AV-1 data for development and assessment of cross section geometric models of faulting at Yucca Mountain (Young et al., 1992) and (ii) to support preliminary assessments of uncertainties related to acquisition and interpretation of seismic data for detection of subsurface geologic features.

In anticipation of seismic surveys conducted to support site characterization activities at Yucca Mountain, the U.S. Geological Survey (USGS) (Brocher et al., 1990) conducted the AV-1 field trial of seismic methods that involved acquisition of 27 line-kilometers of combined 60-fold Vibroseis and chemical-explosion reflection seismic data across the southeastern end of the Amargosa Desert Valley (Figure 1). Reflected energy was recorded over a 15 second time span following the vibration sweep or explosion. Thus, the amplitude record contains reflections from a depth equivalent of 15 seconds (s) of two-way travel time (twtt). Two-way travel time is the time required for an impulse (induced) acoustic wave to travel down to a reflecting discontinuity and return to the recording geophone array at the ground surface. The pathway along which twtt is measured is usually considered to be a normal-incidence ray path.

The interpretations produced here are the result of combined inspection of the amplitude record sections and geometric modeling of fault traces interpreted from the record section. These interpretations are currently being reviewed to determine implications for continued modeling of the Yucca Mountain fault system and for indications of faulting on trend with Fortymile Wash.

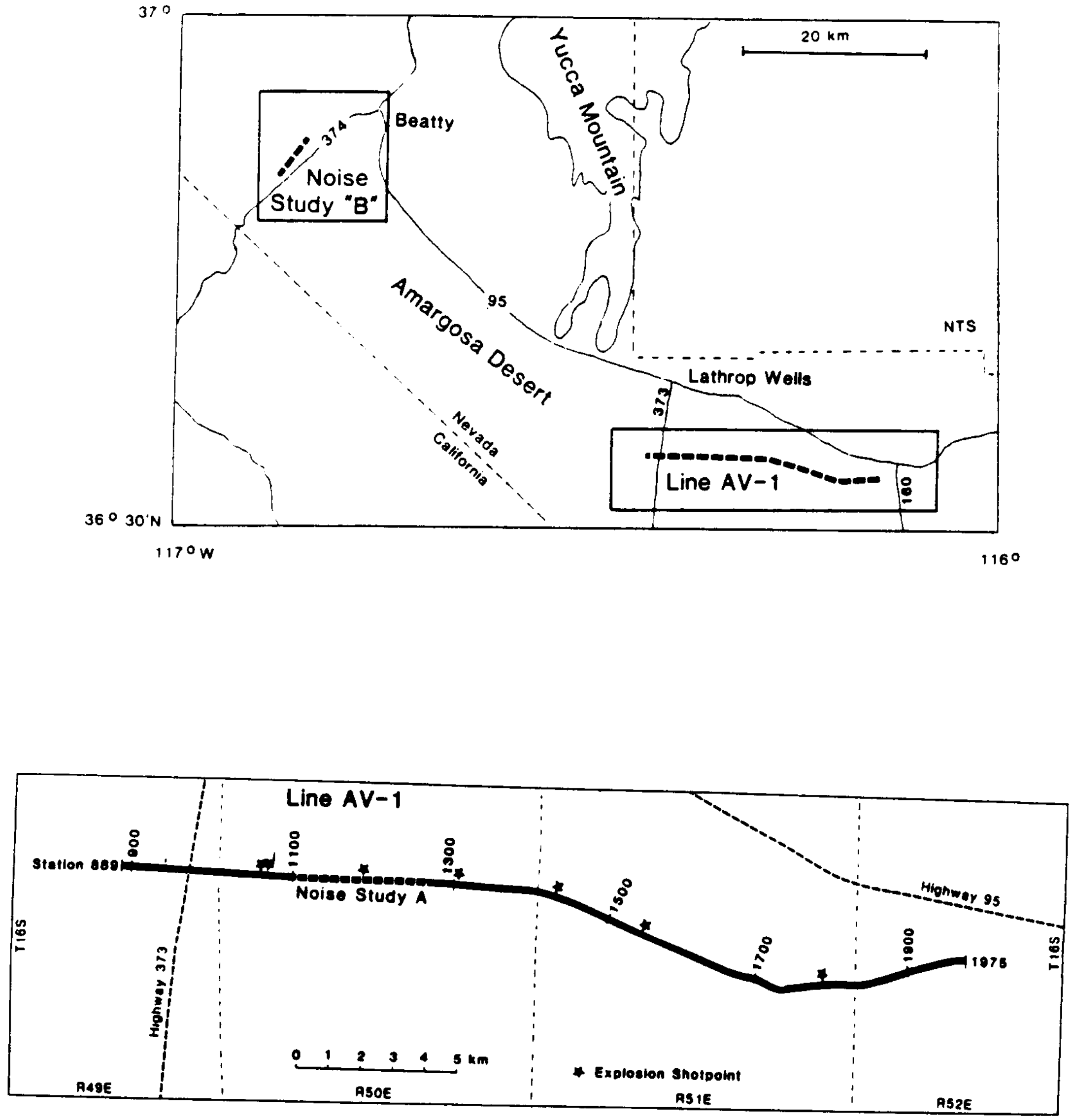


Figure 1. Location maps of AV-1 reflection seismic line. The AV-1 survey was conducted across the southeast flank of the Amargosa Desert Valley (upper map). The strip map (lower map) shows explosion shotpoint locations (stars) and vibration points (numbered tic marks). From Brocher et al., 1990.

2 GENERAL APPROACH

Two basic approaches are used in combination to produce the set of preliminary structural interpretations presented here. In the first approach, complete fault trajectories and fault blocks are interpreted by inspection directly from the record section. The record sections currently available are amplitude displays of reflected energy plotted as two-way travel time along the depth axis against distance along the survey line (horizontal axis). Discrete domains of laterally continuous reflectors are identified initially by inspection of the amplitude display. The position and dip of faults is then interpreted based on visually distinct dip discordance between adjacent packages of reflectors. The resulting interpretation is converted to a depth section using a velocity field compiled from the AV-1 velocity analyses (Brocher et al., 1990) and a coincident refraction survey reported by Mooney and Schapper (1988) and documented in Oliver et al. (1990). The travel-time sections are converted to depth to remove the scale exaggeration and distortion present in the time displays; structural geologic models are best examined and interpreted at true (1:1) scale.

The second approach requires that only a shallow segment of each fault trajectory be picked directly from the record section. Additionally, the geometry and cutoff positions of a correlative reflector must be interpreted in both the hangingwall and footwall of the fault. These shallow interpretations are converted to depth. Deeper fault trajectories are then modeled directly from the shallow fault segment and the interpreted geometry of the hangingwall (Young et al., 1992). The complete fault models are converted back into the time domain for comparison with the record section. Record sections are then examined for evidence of dip discordance along the modeled trajectories of the faults. This is an iterative process that uses the limited predictive capabilities of the models to search for subtle dip discordance in the seismic data display, and in turn allows adjustment of the controlling parameters of the models based on features observed on the record section.

Two basic types of data displays are used to produce initial interpretations of shallow fault trajectories by inspection of the record section. The two types of displays are distinguished on the basis of a post-acquisition processing technique called migration. The record sections are displayed as either unmigrated or migrated. In general, unmigrated common-depth-point (CDP) stacked record sections are used to determine both position and dip of faults. However, down-going seismic waves are diffracted by the up-tilted corners of the east-dipping rotated fault blocks. This diffracted energy is recorded by the receiver arrays and occurs on the amplitude record section as hyperbolic reflection patterns originating at the fault block corners. Shallow fault traces may thus be obscured in the area of the fault block corners. As the corners of the fault blocks essentially mark the position of the bounding faults, it is important to precisely locate the obscured corners on the record section.

To partially remove, or "collapse", the diffraction trains from the stacked data, and to place dipping reflectors in their proper position on the section, a migration step was added to the processing stream by Brocher et al. (1990). Migration of the AV-1 data was done using a finite-difference approximation of the wave equation (e.g., Claerbout 1976; Robinson and Treital, 1980; Robinson, 1983). For the AV-1 data, the migration was done after the data were stacked. Post-stack migration is computationally less expensive, depending on the number of channels stacked (algebraically summed) into each record trace. The AV-1 line is predominately 60-fold; sixty receiver channels are combined into each CDP gather (record trace) on the section. Prestack migration of each individual seismic trace usually results in much higher resolution of geologic features, but is computationally more expensive by a factor approximately equal to the "fold" of the data. Prestack migration of AV-1 would involve at least sixty times the number of individual event migrations. Even so, in structurally complex regions, it is highly recommended that pre-stack migration be used rather than post-stack.

The shallowest point of each individual fault was picked initially on the migrated sections. However, the migrated and nonmigrated data were used together to interpret complete fault trajectories. Migration remains somewhat of a processing art, and it is typically impossible do a single migration step that is appropriate for the entire record section. Thus, while the migrated data may be appropriate for interpretation of a part of the record section, the unmigrated data may contain useful information elsewhere on the section. For the AV-1 data specifically, the migrated record section shows evidence of being "over-migrated" at twtt in excess of about 2.5 to 3.0 seconds. That is, the migration velocity chosen to optimally enhance the shallow reflectors appears to be too high for the deeper part of the section. The result is distortion of otherwise sub-horizontal, fairly continuous reflectors on the unmigrated sections into concave-upward hyperbolas, or "gullwings", near the base of the migrated amplitude record. Consequently, for this study, the migrated data were primarily used to pick shallow fault positions and fault-block dips, while the unmigrated data were used selectively where good reflectors were present on the section.

Ideally, several types of migrations, a range of constant-velocity stacked sections, velocity analyses, and selected types of amplitude, frequency and velocity displays should be used in the interpretation process. Regulatory concerns about uncertainty related to resolution of geophysical methods can be directly addressed by review and assessment of field methods, processing techniques, and display types. Indeed, previous high-resolution reflection surveys conducted at Yucca Mountain (McGovern et al., 1983) yielded marginal results perhaps in part because field methods and processing techniques were not appropriate for geologic and surface conditions at the site (Burkhard, 1986). Use of long receiver-arrays and high-resolution recording methods, rather than stack-arrays, may have attenuated first break signals and filtered the higher-frequency signals necessary to resolve complex shallow structure (Burkhard, 1986). Likewise, the set of interpretations of AV-1 produced in this study depend on a limited suite of processing and data-display techniques. However, the field methods appear to be near optimal, and other options were tested in the field (Brocher et al., 1990). In particular, use of the Vibrosies source, stack-array acquisition and processing methods, exhaustive noise studies, and a large number of closely-spaced receiver channels resulted in good resolution of shallow (< 1.5 s twtt) geologic structures. The AV-1 survey also utilized onsite, real-time processing of shot records to optimize acquisition and recording parameters. Alternative automatic gain control (AGC) windows and bandpass filters were applied to shot records onsite to assess effects of post-acquisition processing, and to adjust acquisition methods accordingly. Thus it is important to keep in mind that results of previous reflection seismic surveys at Yucca Mountain, and to a lesser extent the current set of interpretations of AV-1, have probably not adequately evaluated alternative processing and field acquisition methods and parameters.

3 GENERAL OBSERVATIONS

The primary immediate value of the AV-1 data to structural interpretation of the Yucca Mountain area is that it provides important tests for the following concepts, as discussed by Young et al. (1992):

- Presence of a fault/faults within and on trend with Fortymile Wash;
- Conceptual structural styles and conceptual tectonic models;
- Models of detachment-fault surfaces that may exist below Yucca Mountain.

Major normal fault trends in the vicinity of Yucca Mountain are generally north-south to northeast-southwest, sub-parallel to the overall structural grain of the Great Basin to the north (Scott, 1990; Frizzell and Shulters, 1990). However, the general north-south tectonic fabric of the Great Basin is strongly cross-cut at about the latitude of Yucca Mountain by northwest-trending strike-slip fault systems (Carr, 1984). The AV-1 survey was conducted across the northeastern flank of the Amargosa Desert valley, which is parallel to the cross-cutting strike-slip trend (Figure 2). Thus, the AV-1 survey is appropriately oriented to cross faults that extend southward from the Fortymile Wash-Jackass Flats area into the Amargosa Desert valley. Fault systems buried beneath alluvial sediments in the Amargosa Desert, and evident in the AV-1 data, may correlate with those exposed in bedrock outcrops in the Skeleton Hills, Striped Hills and Specter Range north of the AV-1 line. Earlier geologic studies (e.g., Lipman and McKay, 1965) have inferred faulting in Fortymile Wash based on southward extension into the wash of structures mapped in bedrock exposures north of the Fortymile Wash-Jackass Flats alluvial valley (i.e., Calico Hills, and the Pinnicles Ridge area immediately west of Fortymile Canyon and north of Yucca Wash). Wright (1989) infers a Neogene-age normal fault buried beneath the east flank of the Fortymile Wash-Jackass Flats valley, part of which is coincident with the west flank of Little Skull Mountain. Lipman and McKay (1965) initially considered Fortymile Wash to occupy a graben associated with Basin and Range extensional faulting. Subsequently, Hoover et al. (1982) interpreted resistivity changes along Fortymile Wash to indicate faulting beneath the alluvial cover. From the resistivity data, they identified four north-south trending faults east of Yucca Mountain, with the two central faults of this fault set bounding the graben structure inferred by Lipman and McKay (1965). Of particular significance is the June 1992 Little Skull Mountain earthquake (M5.6). The mainshock focal mechanism indicates primarily normal slip on a fault plane trending northeast-southwest, and with a dip of either about 60 degrees east or about 30 degrees west. The east-dipping focal plan projects to the ground surface about 3.5-4.0 km west of Little Skull Mountain, within the Fortymile Wash-Jackass Flats valley. The west-dipping focal plan projects to the ground surface in the vicinity of the Rock Valley fault zone.

Geologic features are well imaged at less than about 1.5 s twtt on AV-1 (Figure 3a). Discrete domains of continuous, high amplitude reflectors clearly indicate the primarily eastward dip of multiple rotated fault blocks. Major sedimentary basins are indicated by extensive packages of relatively concordant, continuous reflectors. Specifically, important structural geologic features that are apparent directly from both the migrated (Figure 3a) and unmigrated seismic record sections, and have been noted by Brocher et al. (1990) are:

- A stack of continuous, high-amplitude reflectors indicating a sedimentary basin at the west end of the survey (west of station 970), and extending to at least 1.5 s twtt.

- Discrete, east-dipping panels of Paleozoic rocks which are covered by only a thin veneer of valley-filling alluvial sediment between stations 970 and 1310. Each panel is interpreted to

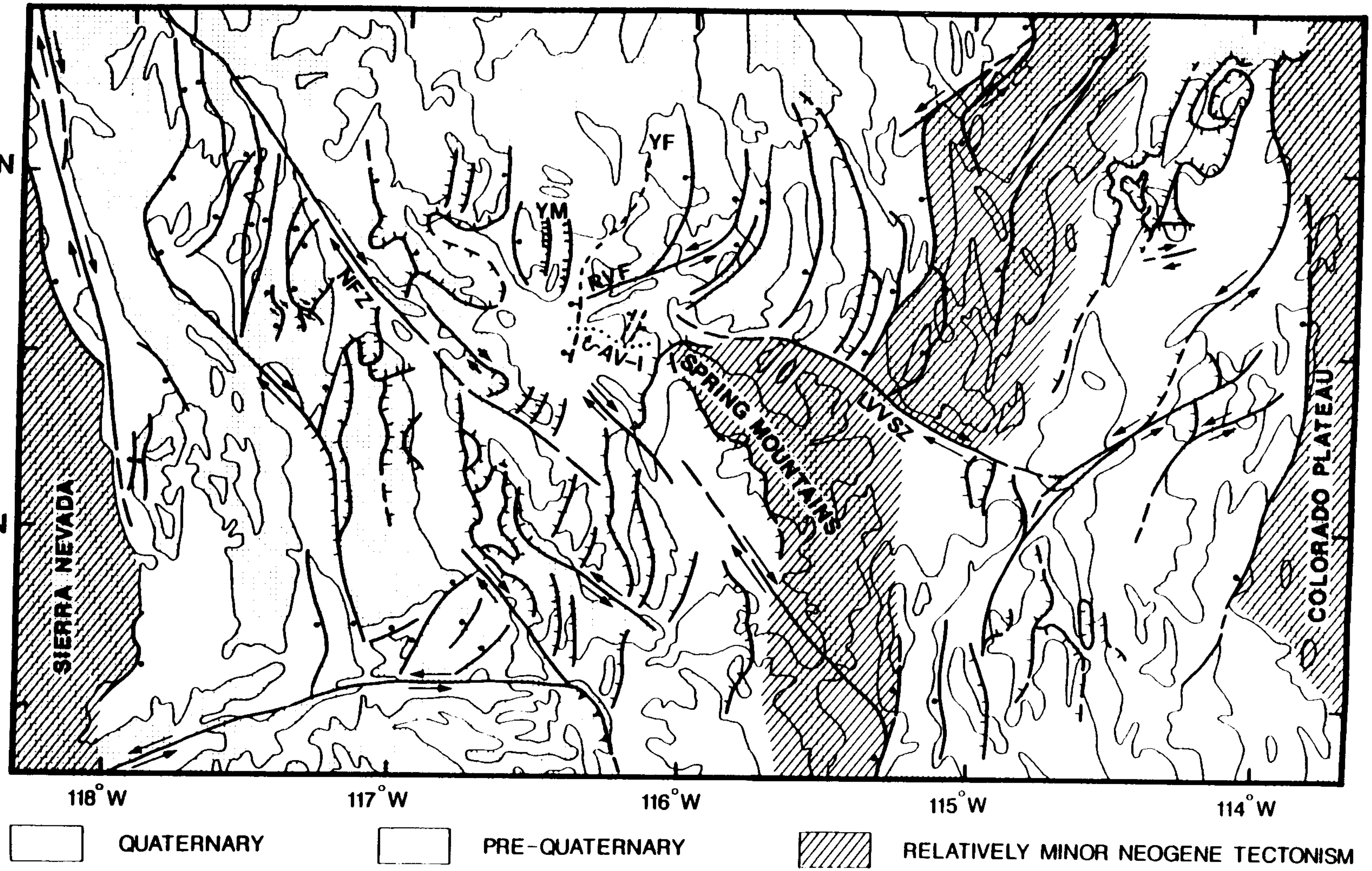
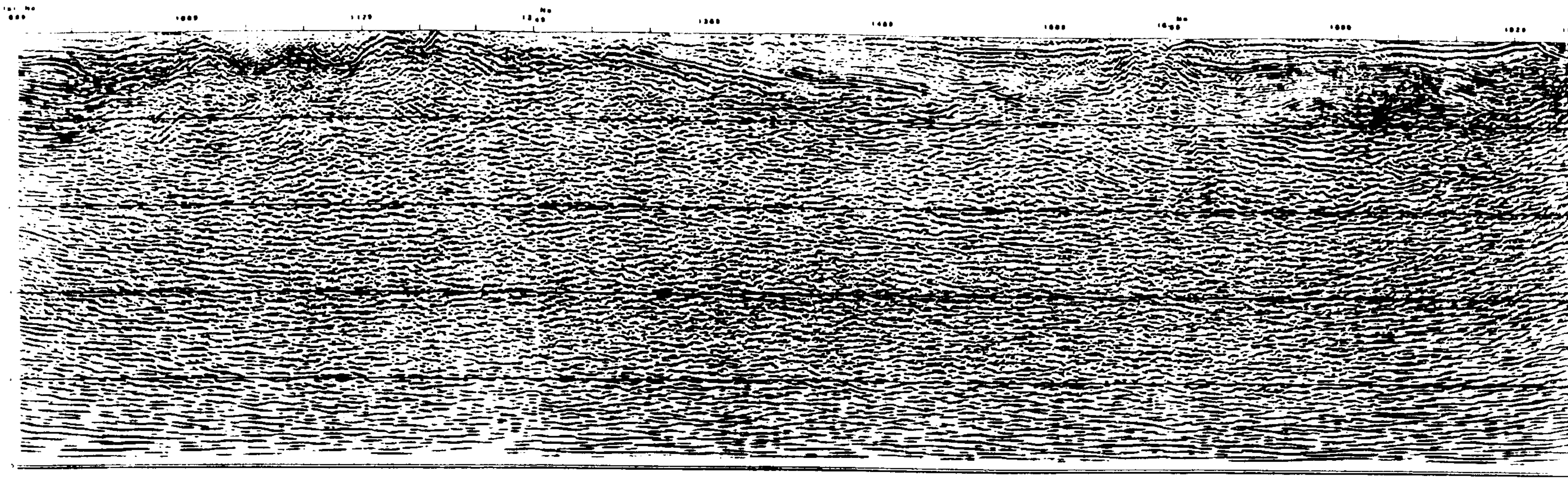


Figure 2. Tectonic map of the Central Basin and Range Region showing major Cenozoic normal and strike-slip fault systems. The northeast-southwest fault shown crossing the west end of the AV-1 line may extend northeast as far as Yucca Flat (YF), or may terminate at the Rock Valley Fault (RVF). YM=Yucca Mountain, NFZ=Northern Death Valley-Furnace Creek fault zone, LVVSZ=Las Vegas Valley Shear Zone. Tic-marks on faults indicate low-angle normal faults, bar-and-ball indicates normal high-angle faults, arrows show direction of strike slip. Modified from Wernicke et al., 1989.

a)



b)

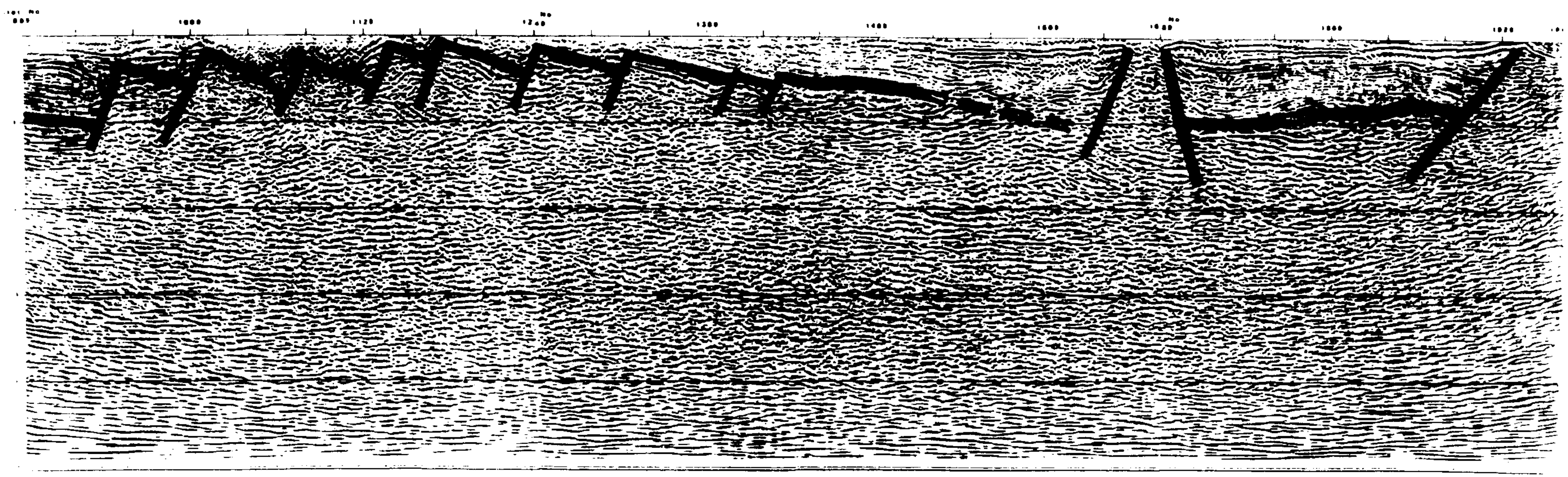


Figure 3. a) Migrated reflection section of the 5 second twtt record. b) Initial interpretation of shallow fault trajectories base on the migrated data. Modified from Brocher et al., 1990.

be a separate fault-block. Blocks are offset by west-dipping reflectors or zones of interrupted reflectors which are interpreted to be normal faults. Cambrian rocks (Bonanza King carbonates) are exposed at the surface in this area immediately north of line AV-1, and are penetrated in shotholes near the west end of the survey (Figure 4; Cornwall, 1972 and Frizzell and Shulters, 1990).

- A deep, well developed half-graben situated between stations 1310 and 1650 and extending through at least 1-1.2 s (twtt). This is the dominant structural feature on the line. The basin is filled with a fairly continuous east-dipping seismic-stratigraphic sequence, and is bounded on the east by a prominent west-dipping normal fault.

- A narrow basement horst between stations 1650 and 1700, composed partially of probable Cambrian age rocks (Bonanza King), interrupts the half-graben basin, and essentially creates two sub-basins that underlie the east half of the survey. This block is probably a buried part of the ridge of Paleozoic rocks extending south from the Specter Range (Figure 3). It is notable also that most geologic maps (e.g., Cornwall, 1972; Stewart and Carlson, 1978) do not show faults bounding this ridge.

- A graben between stations 1700 and 1925, east of the basement horst, with generally shallowly west-dipping reflectors extending to a depth of 1-1.2 s (twtt). A well-developed roll-over fold exists on the east flank of this graben.

A summary depiction of these features is given by the simple interpretation of shallow reflectors shown in Figure 3b. General conclusions drawn from this cursory examination of the data are:

- A major, basin-bounding structure exists at the west end of line AV-1, which is along the trend of an inferred zone of faults within the Fortymile Wash-Jackass Flats area (Young et al., 1992 and Figure 4).

- The structural style exemplified by the interpretation from stations 970 to 1650 is in accord with that utilized to construct the geological cross-sections in Young et al. (1992).

- Further, the heterogeneity of dips in adjacent fault blocks precludes the use of a simple domino-block model (Davison, 1989). This conclusion is further supported by geometric constraints imposed by the widths of individual fault-block dip panels and the elevations of their west (updip) corners (see explanation in Figure 5).

The relatively closely-spaced set of west dipping faults and east dipping fault blocks that underlie the west half of the AV-1 survey are notably similar in shallow structural style and scale to those that comprise Yucca Mountain (Scott, 1990). The width of individual fault blocks (about 1.5 km—2.5 km) that is, the spacing between faults, is also quite consistent with that observed at Yucca Mountain. The overall width of the train of east dipping fault blocks (approximately 10 km) is about the same as the Yucca Mountain fault system measured between the Windy Wash and Paintbrush Canyon faults (10 km—12 km), across the south half of Yucca Mountain. The spacing between the major west dipping bounding fault of the graben structure (at about station 1935) and the west-end basin (station 889) on AV-1 is about the distance (25 km—30 km) from Little Skull Mountain (the east flank of the Fortymile Wash valley) to Windy Wash (the east flank of Crater Flat valley). The half-graben valley on AV-1 (between stations 1360 and 1680) is about 8 km wide, approximately the same as Fortymile Wash-Jackass Flats measured northwest from

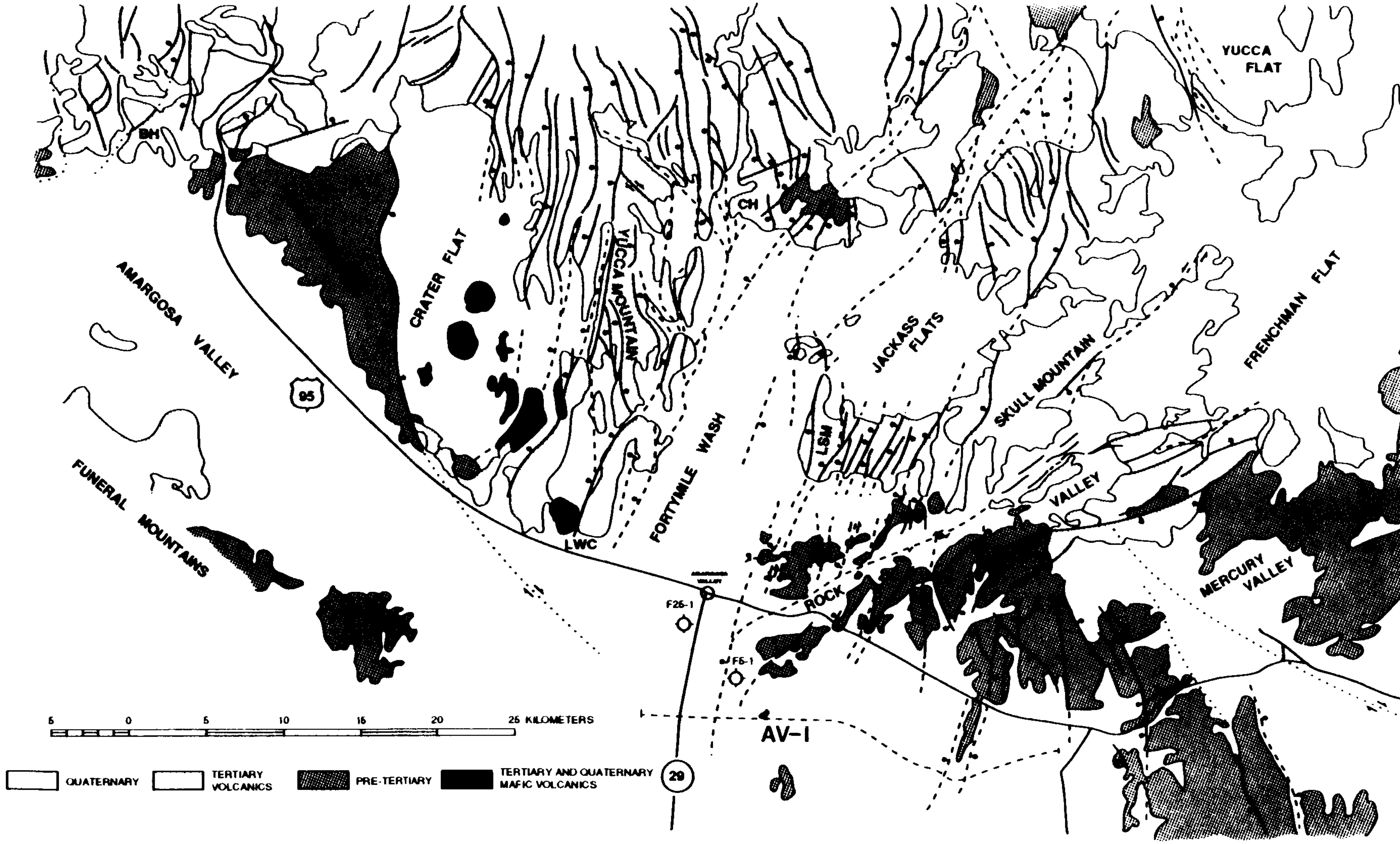


Figure 4. Tectonic map of the Yucca Mountain region. Surface traces of fault zones imaged on the AV-1 line are projected northeast and southwest from the line. Faults and outcrop patterns compiled from Maldonado (1985), Cornwall (1972) and Frizzell and Shulters (1990). CH = Calico Hills. BH = Bullfrog Hills. F25-1 and F5-1 are exploratory borehole locations. Dashed lines are traces of buried faults. Dotted lines are traces of inferred faults.

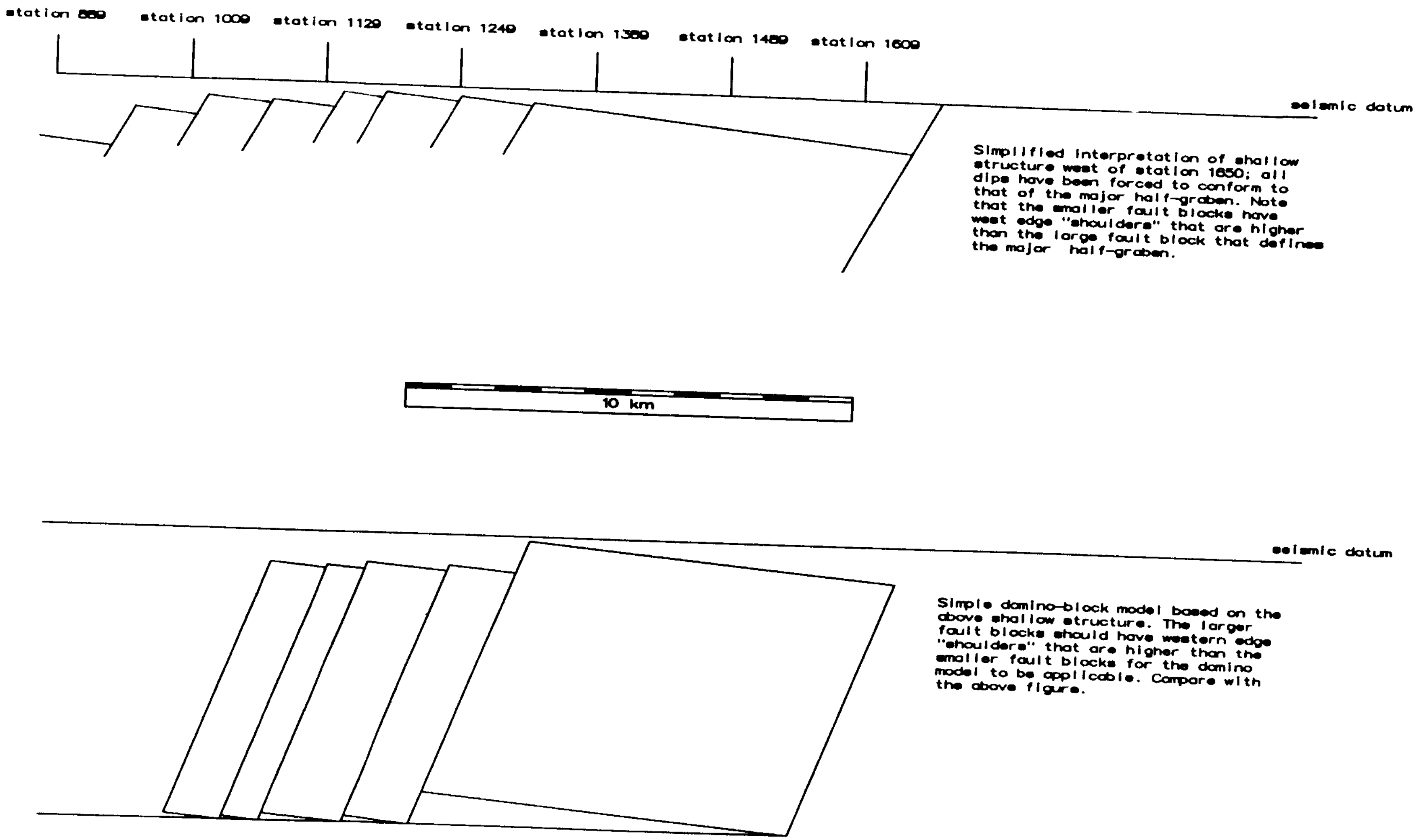


Figure 5. Constraints on the domino model of faulting for structures imaged on AV-1. Upper figure is a simplified interpretation of AV-1 in which all fault-block dips are assumed to be uniform and conform to the dip of the half-graben structure. The lower figure is a simple domino-block model consistent with these assumptions. In the model, note that block rotations consistent with the assumed dips causes displacements that are incompatible with the interpretation.

Little Skull Mountain to Busted Butte. Essentially, the geologic structures buried beneath this part of the Amargosa Desert closely resemble the Yucca Mountain area. These structures are probably about what Yucca Mountain would look like on a seismic survey if it were buried rather than exposed at the surface.

The amplitude displays are difficult to interpret below about 2.0 s twtt; however, the reflection patterns seem more consistent with a conceptual model of low-angle detachment, rather than high-angle (domino-style) models. In particular, there are obvious sub-horizontal and low-angle discontinuities between reflector sequences. These may variously be interpreted as stratigraphic unconformities, extensional normal faults, or older contractional structures. There are no obvious high-angle discontinuities that extend below about 1.5 s twtt.

A simple geometric test applied to the AV-1 data (Figure 5) indicates the shallow fault block geometries are not consistent with a basic domino model. The basic domino model requires that each of the fault blocks have the same dip. Fault block dips on AV-1 are clearly not consistent. Even if block dips are forced to be consistent, to approximate a domino model,(Figure 5), block rotations required to match actual dips on AV-1 drive the west corner of the half-graben block considerably higher than the group of small blocks on the west side of the survey. Inspection of AV-1 shows that the culmination of the smaller blocks is actually at a higher elevation than the updip shoulder of the half-graben. With the data currently available, the AV-1 survey will not support a domino fault model. These results are supported by more comprehensive geometric analyses of alternative models of faulting at Yucca Mountain (Morris et al., 1992). Consequently, models of faulting developed here are based on a detachment style of extensional deformation. However, alternative interpretations are developed, including models of single and multiple detachment systems.

3.1 Velocity Model

Velocity models (Figure 6) required for time-depth conversion and analysis of AV-1 in the depth domain are given by Brocher et al. (1990). Results of the seismic refraction survey used by Brocher et al. (1990) in the form of a depth-domain velocity model (Mooney and Schapper, 1988), provide some velocity control down to approximately 2 s twtt (Figure 6). The resolution of this model is coarse, but it does provide reliable velocities for the valley-filling alluvial sediments and any (presumed) Tertiary volcanic and sedimentary rocks in the basin. Velocity ranges for this material [2.2—3.4 kilometers per second (kps)] are consistent with velocities computed for a seismic refraction study conducted in the Crater Flat valley—Yucca Mountain area (Ackerman et al., 1988).

3.2 Well and surface data

Additional constraints are provided by two shallow exploratory boreholes and mapped surface geology. The Felderhof 25-1 and 5-1 wells were drilled north of line AV-1 as part of a petroleum exploration program (Figure 4). Paleozoic carbonates were encountered in both wells, at a depth of 2,200 ft (670 m) in 25-1 and at a depth of 1,200 ft (366 m) in 5-1. Assuming a NNE-SSW structural trend, these wells project onto line AV-1 between stations 940-960 (25-1) and 1080-1100 (5-1). Based on the projected borehole depths, and using a velocity of 2.75 kps for the surface-Paleozoic interval (valley-fill sediments), the reflector representing the top of the Paleozoic (and presumably the base of the Tertiary section) should be at approximately 0.48—0.5 s (twtt) in well 25-1 and 0.27-0.3 s (twtt) in well 5-1. These estimates are in good agreement with interpretation of the base-Tertiary reflector on the amplitude record section (Figure 3b).

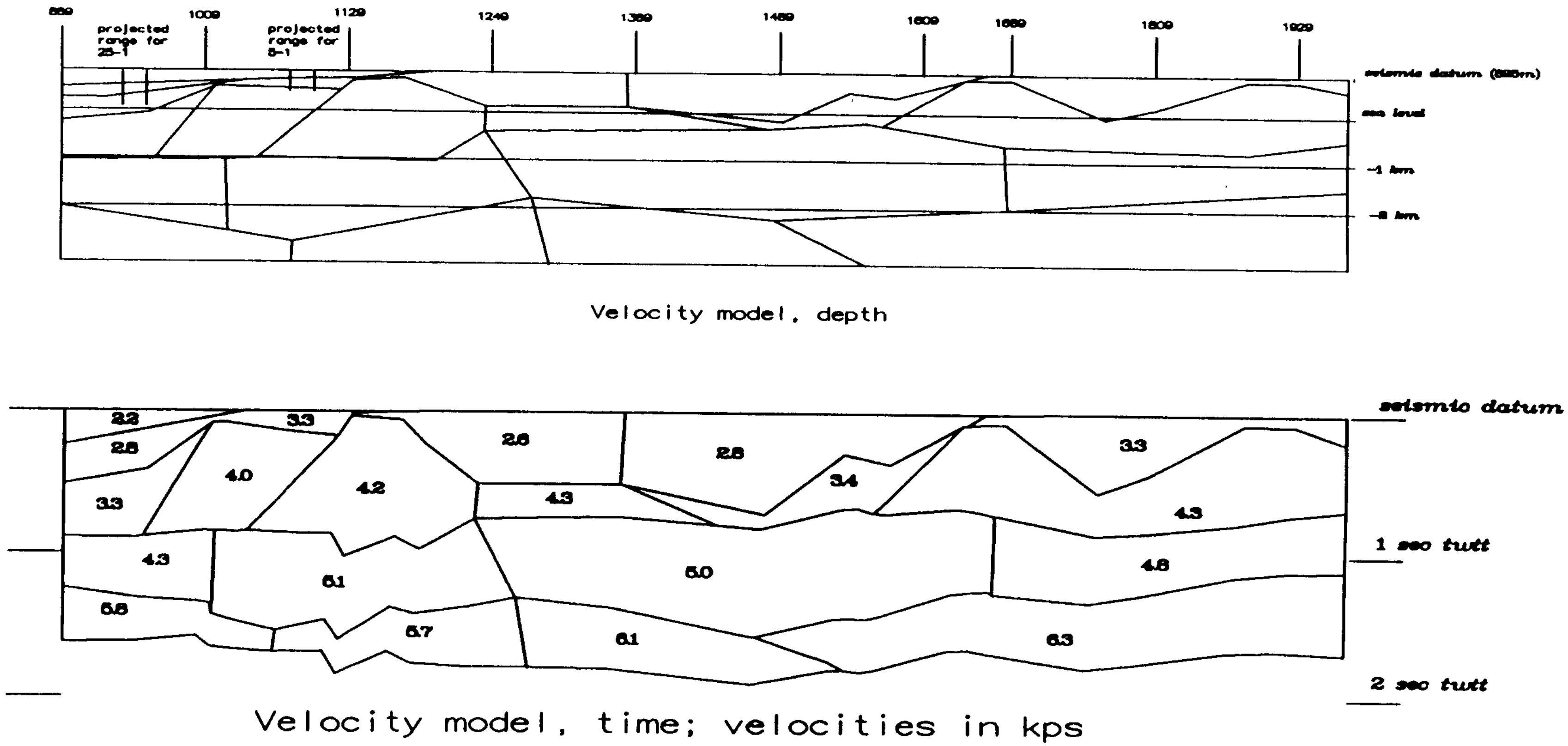


Figure 6. Velocity model of the shallow crust along the AV-1 survey. The model is shown in depth (upper figure) as digitized from Brocher et al. (1990), and as converted to twtt for this study (lower figure). Time-depth conversion assumes vertical ray-path and interval velocities as shown in the twtt section.

The geological nature of the two principal structural highs (at station 1689 and between stations 1129 and 1209) on AV-1 (Figure 3b) can be inferred from nearby outcrops (Figure 4); both are likely to be predominately Cambrian Bonanza King Formation. On all of the interpreted seismic sections that follow, the key stratigraphic reflector highlighted by the thick line is the unconformable base of the Tertiary section, which is coincident with the eroded top of the Paleozoic section.

4 STRUCTURAL INTERPRETATIONS

The largest, best-imaged, and most complete structural feature on line AV-1 is the half-graben between stations 1310 and 1650 (Figure 3). This structure was used to model an initial set of fault trajectories and a range of depths to detachment for the set of major structures imaged on the line. Geometric models of the overall fault trajectory and computation of detachment depth follow the approach documented by Young et al. (1992), assuming:

- The east-dipping graben-base shown in Figure 3b is the eroded top of the Paleozoic section (i.e., the base-Tertiary unconformity);
- The top of the Paleozoic was sub-horizontal at the approximate horizontal seismic datum (0.0 twtt) of 825 m (Brocher et al., 1990) before fault movement;
- The shallow segment of the master fault (at approx. station 1669) is as shown in Figure 3b;
- Seismic velocities in the Tertiary valley and basin fill range from 2.8—3.4 kps (Brocher et al., 1990; Figure 6).

4.1 VERTICAL SHEAR

Utilizing vertical shear as the deformation mechanism for the entire hangingwall block of the half-graben bounding fault, and a selected set of interpretations of the hangingwall and footwall cutoffs of the marker horizon (top Paleozoic) the detachment elevation varies from -5.2 km to -8.6 km (Figure 7). This range approximately encompasses the interpreted maximum and minimum extensional-area configurations of the hangingwall block. The set of detachment models thus includes the maximum and minimum detachment depths for vertical shear deformation (Young et al., 1992). Using seismic velocities of 5.3—5.5 kps for the pre-Tertiary sections, these depth ranges convert to a twtt range of 2.6—3.4 seconds.

4.2 OBLIQUE SHEAR

West of station 1310 (Figure 3) several small normal faults dip approximately 66 degrees west. These could be interpreted as indicative of the hangingwall deformation mechanism. That is, the smaller fault blocks may be a mechanism by which the half-graben block conforms to the shape of the underlying fault surface. To test this thesis against the seismic record, 66-degree synthetic was used as the shear angle to model the fault trajectory and depth to detachment (Figure 7). Detachment elevations from this mechanism are -17 to -34 km, which represent twtt depths of 5.2—9.2 s for sub-Tertiary velocities of 6.5—7 kps. As explained in the discussion below, the record section does not support high-angle faults extending to this depth range.

4.3 INTERPRETATIONS OF DETACHMENT FAULT SYSTEMS

Faults are most precisely positioned on the record section by combining the unmigrated and migrated data. For example, the half-graben bounding fault can be located beneath station 1689 by finding the peak (source) of the hyperbolic diffractions at the top of the fault block on the unmigrated section,

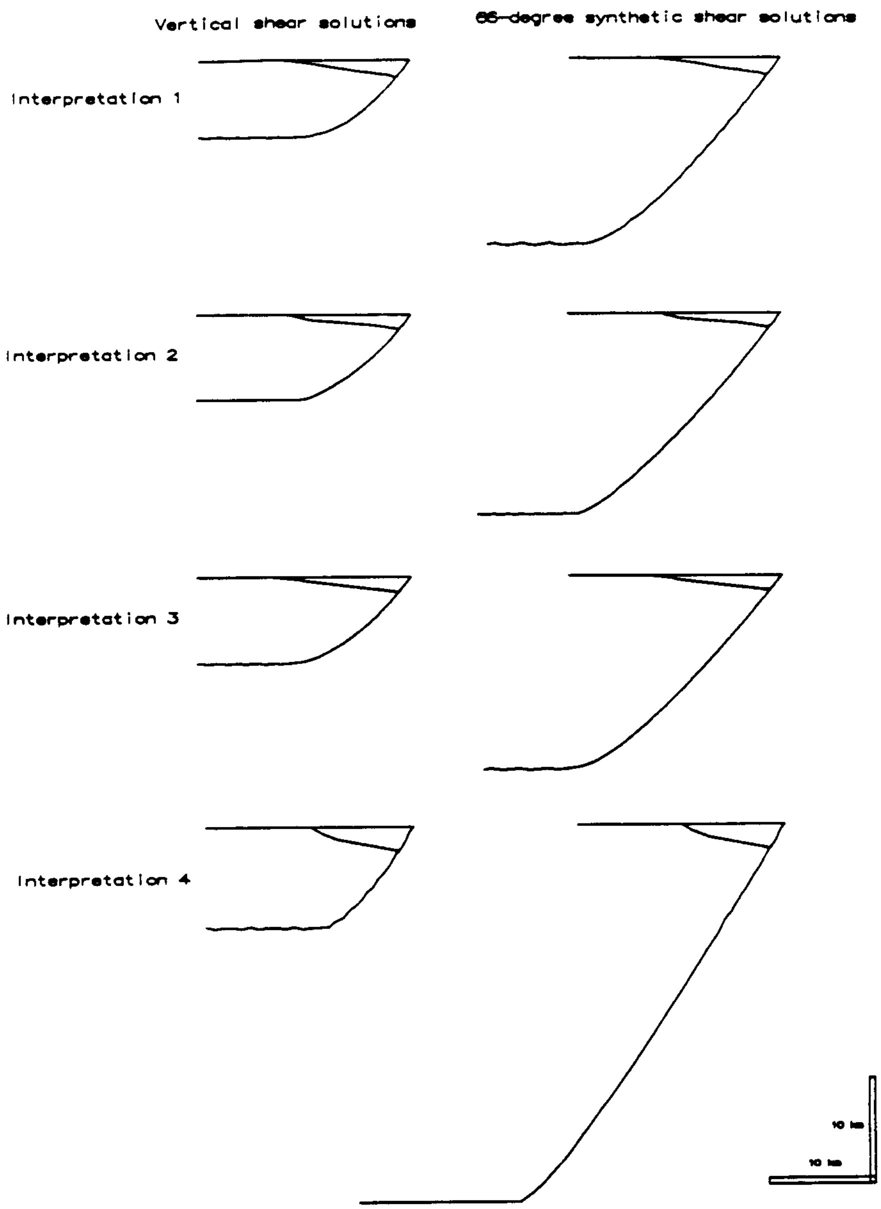


Figure 7. Computed range of depths to low-angle detachment for the half-graben structure. The column of solutions on the left uses vertical shear as the hangingwall deformation mechanism; those on the right use 66° synthetic shear. Each row of models shows alternative interpretations of the half-graben hangingwall geometry; deeper detachment interpretations are toward the bottom of the column. Horizontal and vertical scale bars are 10 km.

and then tracing the truncations of sub-horizontal reflections on the migrated data to depth (Figure 8). There are a number of inclined reflectors between twtt depths of 1 and 3.3 s, and these are probably partial images of listric fault surfaces. Unfortunately, none of the data below about 1 second twtt is clear, and the complete trajectories of faults cannot be traced with certainty. There are three reflector sets that are good candidates for detachment images; these sub-horizontal zones of reflectors occur at twtt intervals of 1.1—1.2 s, 2.4—2.6 s, and 3—3.3 s.

Single-detachment interpretations fall into two broad categories, those that utilize a major detachment at 2.4—2.6 s twtt and those that use a detachment at 3—3.3 s twtt (Figure 9). Detachment levels deeper than these are difficult to justify on the basis of the available reflectors on AV-1. Detachment models using the 1.1—1.2 s reflectors are part of the multiple detachment interpretation discussed below.

A small wedge of high-velocity (3.4 kps) basal basin fill (probably Tertiary sedimentary rocks) is included in the velocity models, based on the refraction model used by Brocher et al. (1990; Figure 6). This horizon may be significant for depth conversion, and therefore geometry, of the top of the Paleozoic marker. Additional work in seismic sequence analysis should be done to interpreted the nature of this material, and to determine the relative stratigraphic position of this sequence. This work is not within the scope of the current study.

4.3.1 3—3.3 second detachment

Figure 10a shows the digitized time-velocity model using the 3-3.3 s twtt reflector set as the base detachment. An estimated sub-Tertiary average velocity of 5.7 kps is assumed for the 3.3 s twtt interval, and was used for this depth-conversion. The average velocity used for depth conversion is estimated from the interval velocities shown on the refraction model (Figure 6). Although the refraction model is the best velocity data currently available, reflection velocity analyses would substantially improve the accuracy of the depth conversion. The current depth conversion gives an elevation of approximately -8 km for the detachment (Figure 10b). Fault trajectory modeling based solely on the shallow geometry of the base of the Tertiary and the half-graben bounding fault indicates that this depth of detachment can be justified if the hangingwall was deformed by 80—82 degrees synthetic shear.

4.3.2 2.4—2.6 second detachment

Interpretations utilizing a 2.4—2.6 second twtt detachment level (Figure 11a) are supported by fault models based on the shape of the major half-graben, assuming vertical shear as the hangingwall deformation mechanism. An estimated sub-Tertiary average seismic velocity of 5.35 kps is assumed for the 2.6 s twtt interval. The average velocity assumed for this interval is somewhat less than that used for the deeper 3.3 s twtt interval. The available refraction velocity model is not sufficient to resolve interval velocities within the twtt ranges of interest. However, the average velocity estimates are consistent with the shallow interval velocities shown on the refraction model (Figure 6). These interpretations are consistent with a detachment elevation of -5.2 to -5.5 km (Figure 11b). Listric fault geometries and detachment depths recently determined for the Yucca Mountain fault system are also in this depth range (Young et al., 1992).

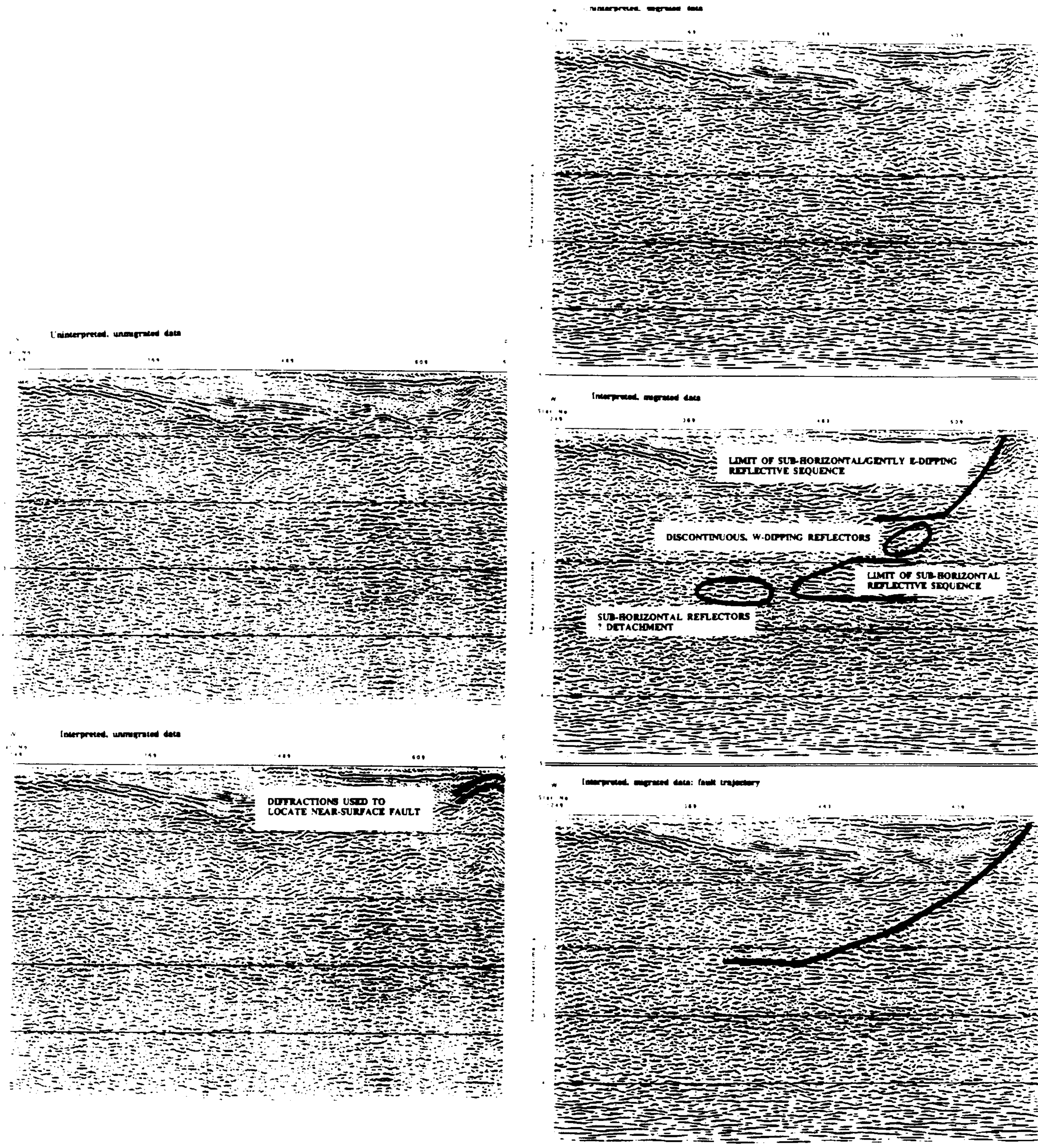


Figure 8. Interpretation of the major half-graben bounding fault by inspection of the record section.

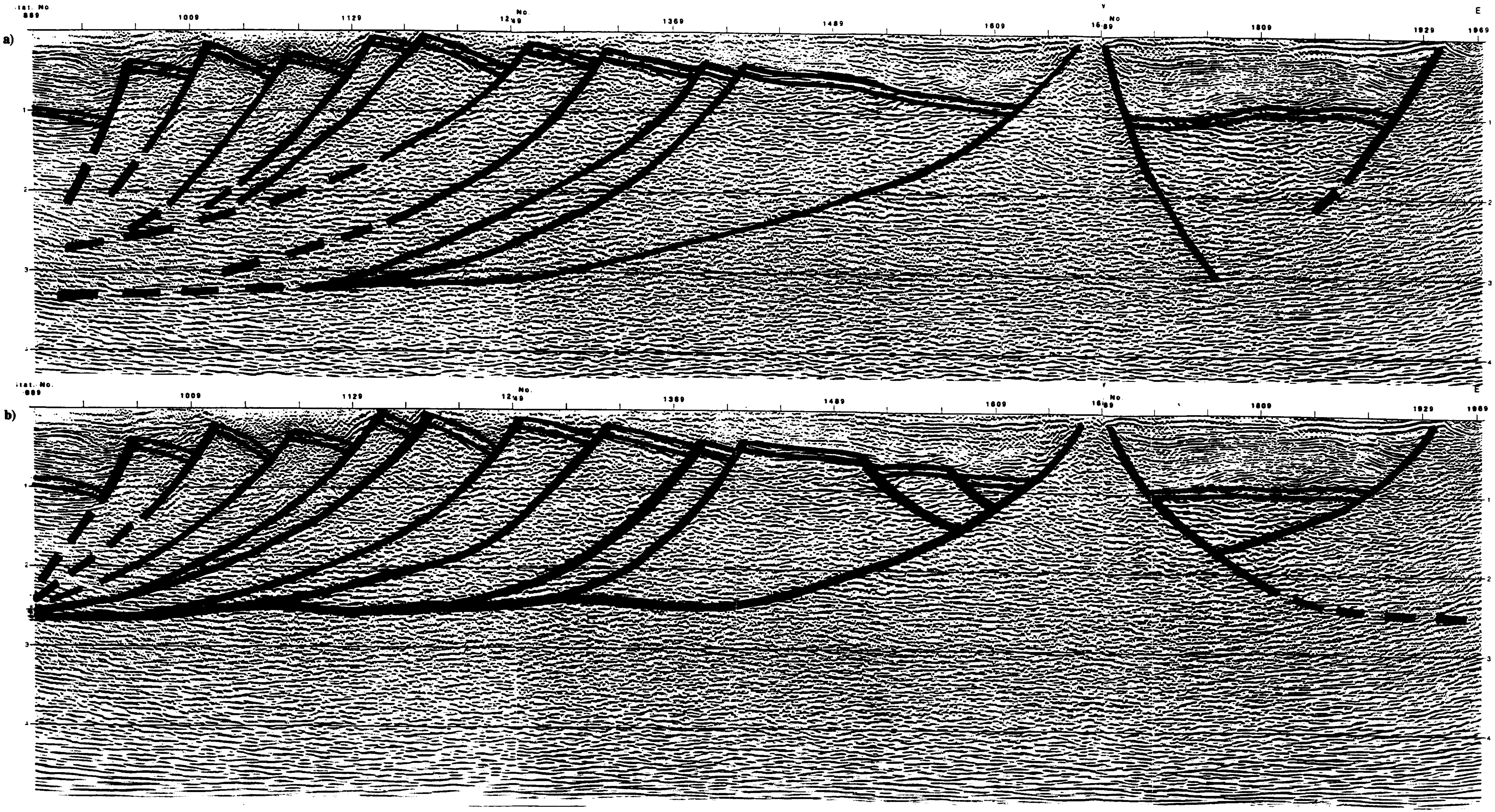


Figure 9. a) Interpretation of 3—3.3 s (twtt) detachment from migrated seismic record, b) Interpretation of 2.4—2.6-s (twtt) detachment from the migrated seismic record.

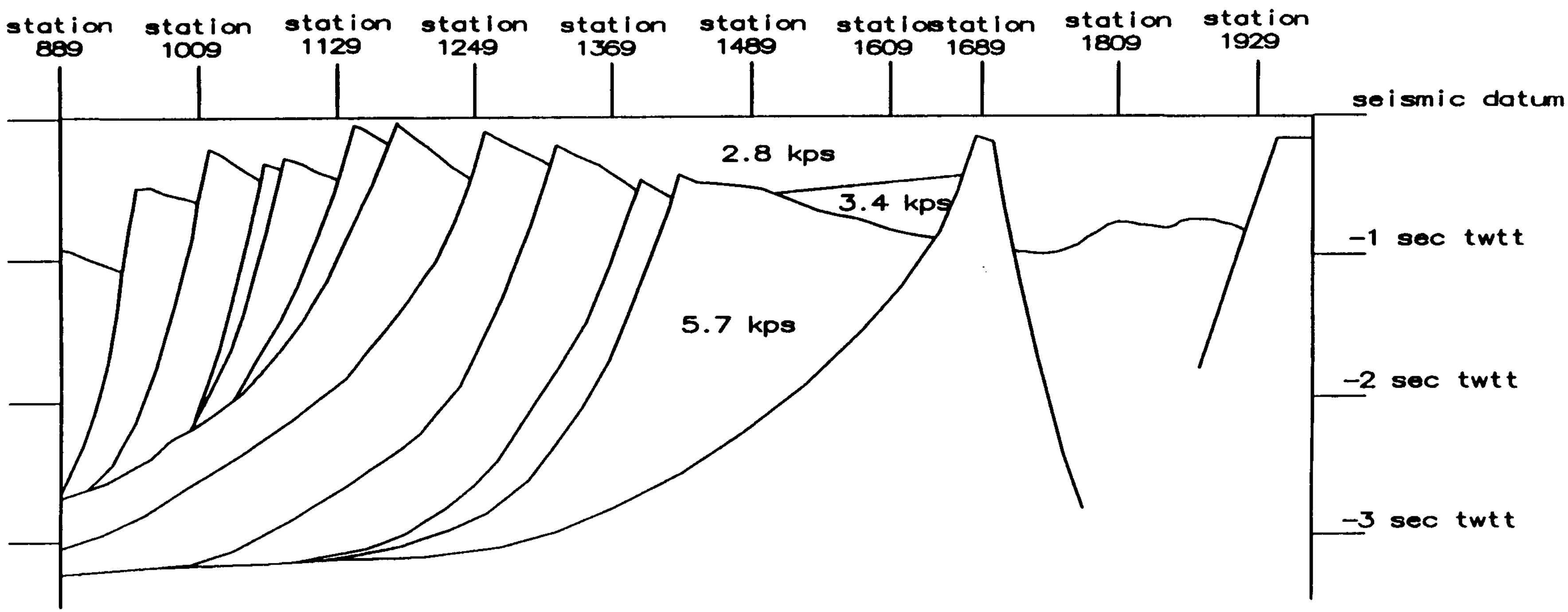


Figure 10a. Digitized 3—3.3 s (twtt) detachment interpretation. Velocities (kps) shown (from Figure 6) are used to convert the model to depth domain.

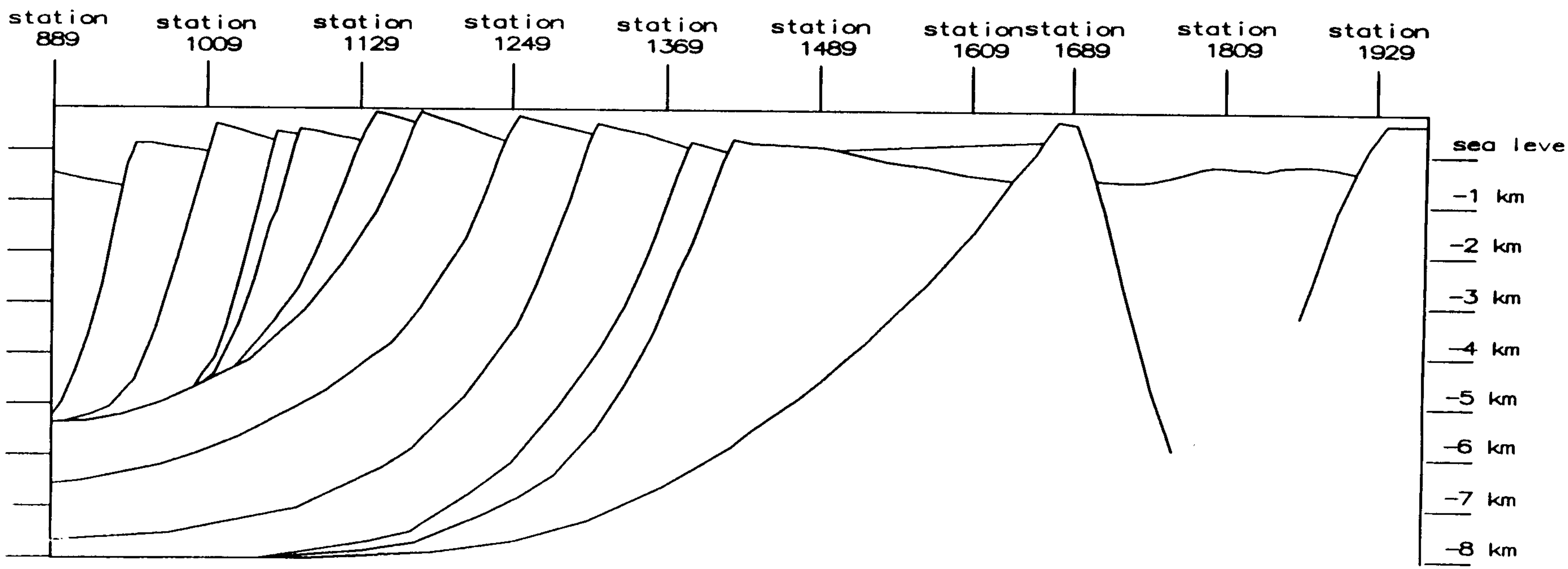


Figure 10b. Depth model of 3—3.3 s (twtt) detachment interpretation. Fault trajectories from the group of fault blocks at the west (left) end of the model detach at a shallower level than the large half-graben structure.

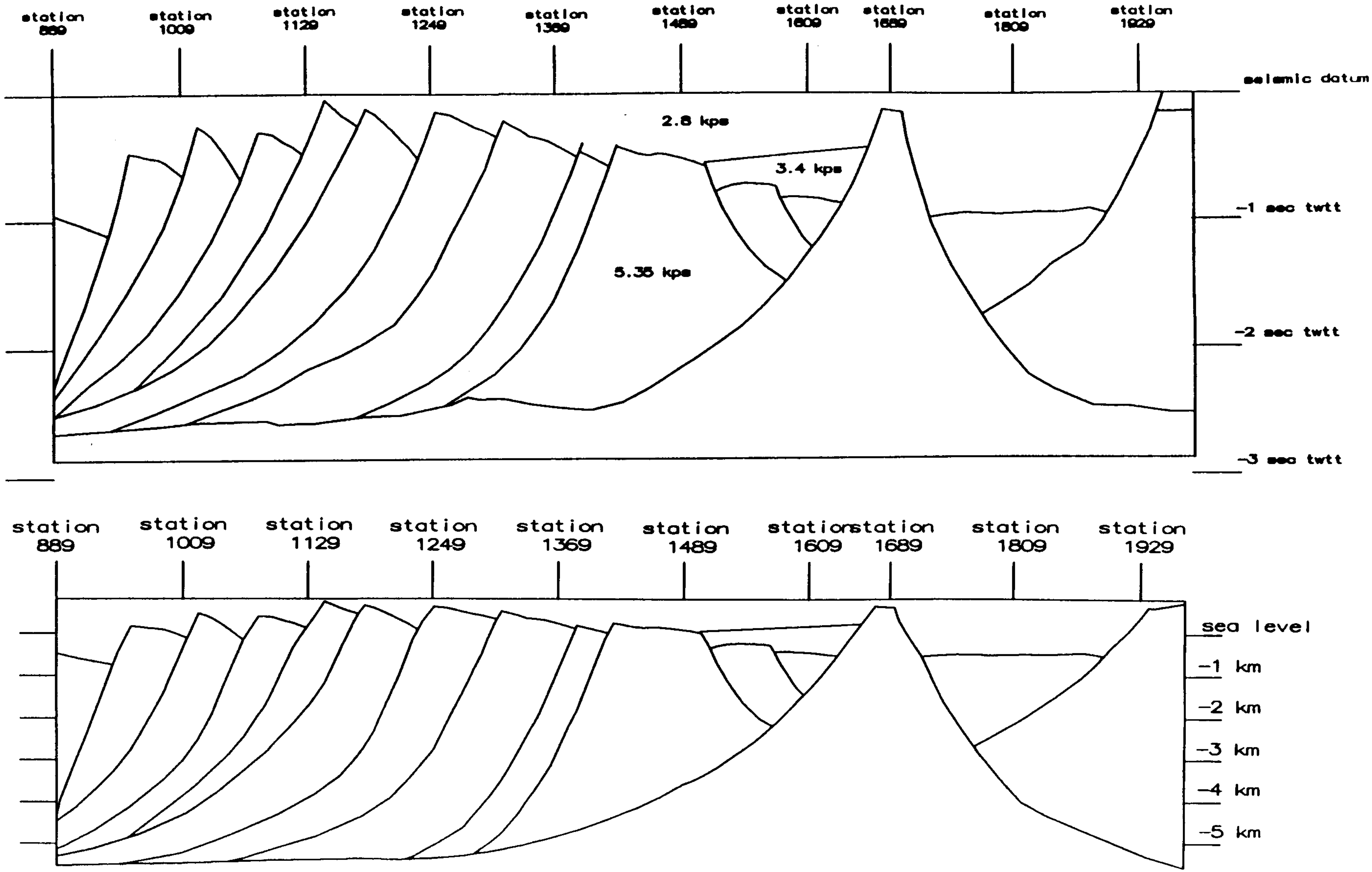


Figure 11. a) Digitized 2.4—2.6 s (twtt) interpretation. Velocities (kps) shown (from Figure 6) are used to convert the model to depth domain, b) depth model of 2.4—2.6 s (twtt) detachment interpretation. Most of the fault trajectories detach at a common level.

4.3.3 Multiple-detachment models

In attempting to fully restore (retro-deform) the depth-converted interpretation shown in Figure 11b trajectories could not be modeled for the faults west of station 1449 that would flatten and merge at elevations of -5.2 to -5.5 km; they all gave consistently shallower balanced trajectories based on their hangingwall geometries. As noted above, upon inspection, a series of moderately well-defined reflectors can be seen at twtt depths of 1.1—1.2 s in this area of the record section. The subsequent array of fault trajectory models can be fitted to a detachment at an elevation of approximately -2 km. Upon time-conversion, using velocities of 2.75 kps for the Tertiary valley fill and 5.35 kps for the sub-Tertiary, this equates to a depth of approximately 1.1—1.2 s twtt (Figure 12a).

The resulting balanced multiple-detachment model has some interesting characteristics. Because of the ramp-flat form of the interpreted fault geometry, forward modeling of the section results in development of a hangingwall syncline between stations 889 and 1129. As deformation proceeds, this syncline grows and migrates to the west end of the section. Figure 12b shows the modeled stratigraphic growth horizons within this basin; it has marked asymmetry, with very steep west dips at its east margin. This feature would image on a reflection seismic section very much like a fault. The presence of such a hangingwall synclinal basin does not preclude a fault in this part of the section, neither does it negate the necessity for a major structure on trend with Fortymile Wash (Figure 12b). Indeed, it is likely that the Paleozoic rocks at this point in the section are not folded in such a ductile fashion as the model suggests, but contain an array of quasi-penetrative (distributed), perhaps upwardly and downwardly blind (terminating), normal faults. Figure 13 shows the 5 second migrated seismic record section interpreted using the multiple detachment model.

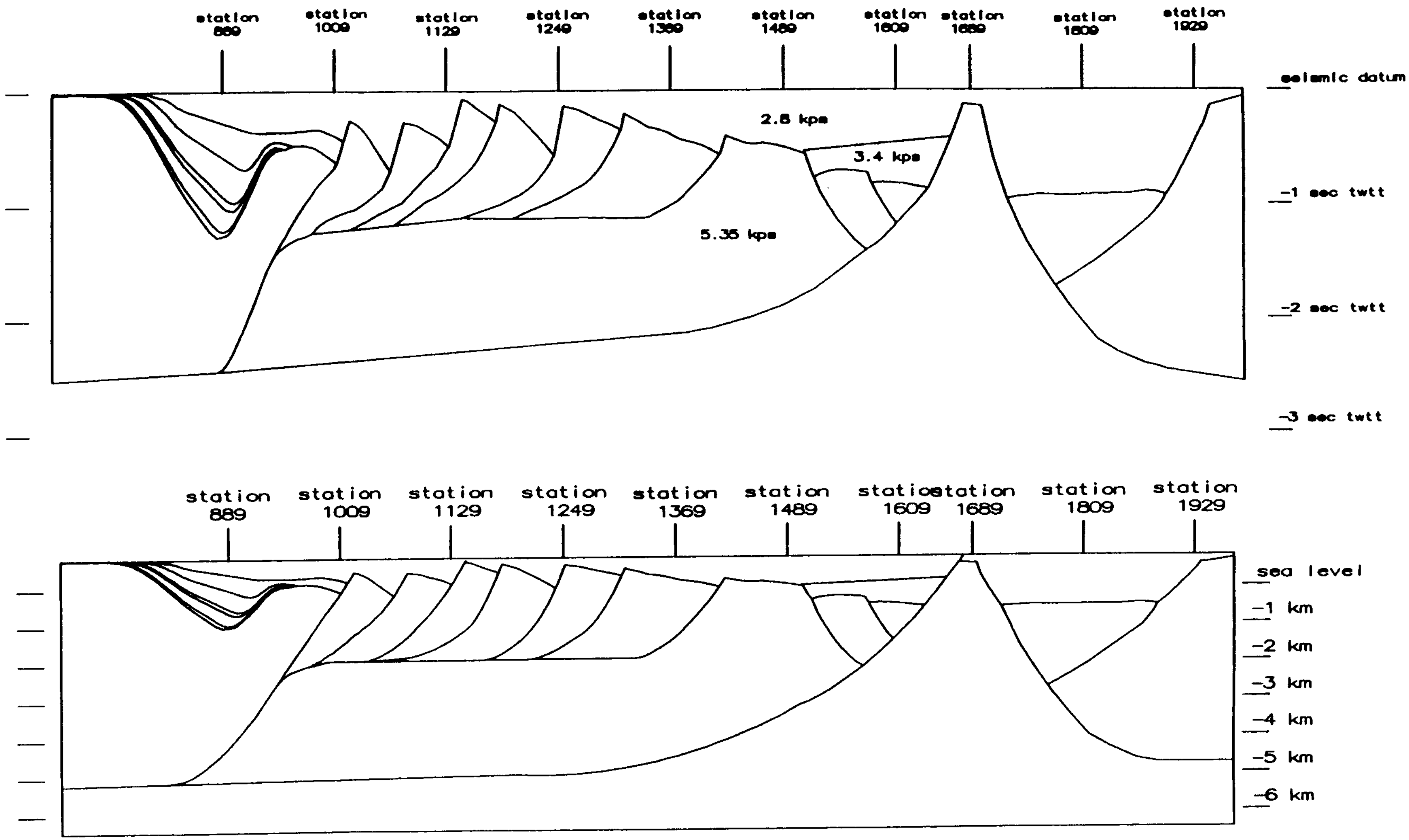


Figure 12. a) Multiple detachment model. Fault-block dips are forward-modeled using vertical shear. Dipping horizons shown beneath station 889 are modeled intra-Tertiary stratigraphic growth horizons that show the predicted form of reflectors in the hangingwall syncline basin, b) time domain conversion of multiple detachment model. Velocities (kps) shown (from Figure 6) are used to convert (a) to time domain.

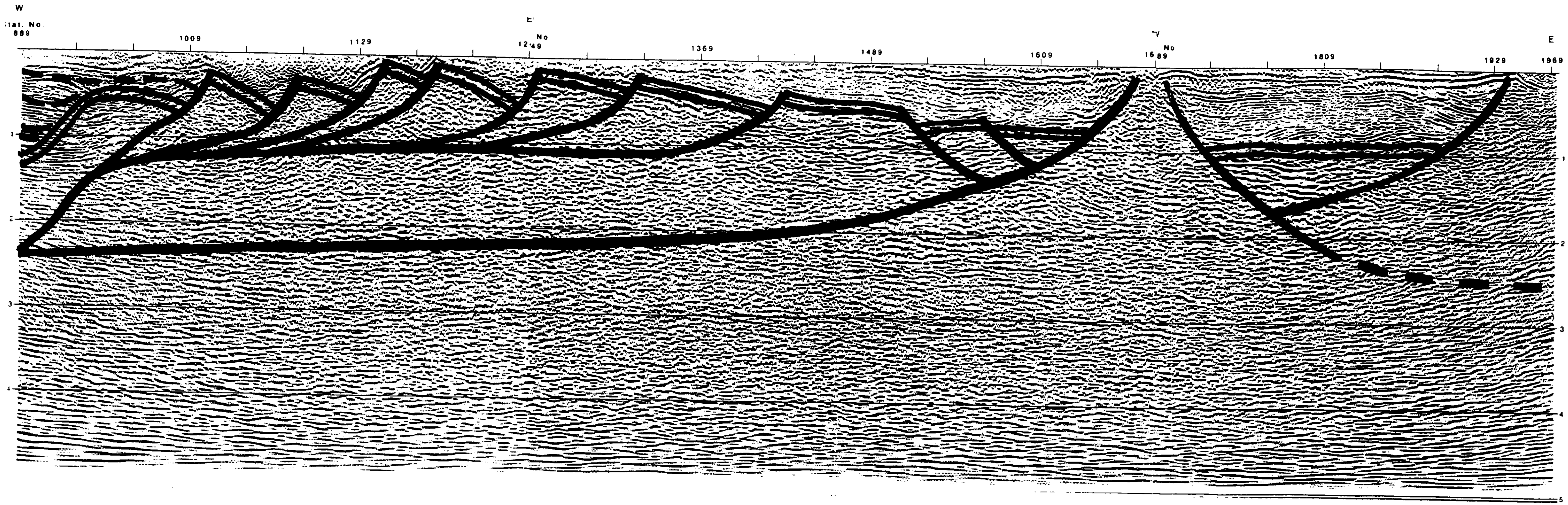


Figure 13. Time-domain conversion of multiple detachment model on migrated 5 s (twtt) section.

5 DISCUSSION

The highest quality data available from AV-1 are from within 1—1.2 s twtt of the surface (Figure 3b). The key modeling parameters available within this twtt range are near-surface fault position and dip, stratigraphic cut-off positions, and dips of major fault blocks. Velocity data are also most reliable in this travel-time range. Although this seems to be a superficial view of the structure, there is significant information in these geometries. On the basis of the geometry of the major half-graben between stations 1310 and 1650, the master fault responsible for the structure can be modeled. Depending upon hangingwall deformation mechanism, this modeling predicts detachment elevations of -5.2 km to -34 km. This extreme range can be substantially narrowed by considering the next best set of data from the seismic record section: sub-horizontal reflectors representing possible detachments within the deeper crust. There are three good candidates for this detachment: 1.1—1.2 s, 2.4—2.6 s, and 3—3.3 s twtt. Using reasonable velocities for the pre-Tertiary section (Figure 6), this narrows the potential elevation range for major detachments to -5.2 km to -8 km. This range is again constrained by further consideration of the data available from the record section. The half-graben bounding fault has an interpreted trajectory that is moderately well constrained by the seismic data (Figure 8). Interpretation of the seismic record section provides a detachment elevation that is in close agreement with vertical shear modeling: -5.2 km. The observed compatibility of modeled and interpreted fault trajectories suggests that vertical shear is a valid deformation mechanism in this terrain, and that extensional deformation expressed on AV-1 is consistent with that observed at Yucca Mountain.

Multiple detachment interpretations provide an interesting alternative to single detachment models. The multiple detachment idea was driven by attempts to restore the fault blocks between stations 970 and 1310. These smaller faults will not restore from the deeper detachment level. Considering the geometry of the top-Paleozoic marker to be the best available data, these markers were used to determine restorable fault trajectories with the result that a shallow detachment (at 1.1—1.2 s twtt) is predicted for the set of small fault blocks. Perhaps the most interesting corollary of this model is the generation of an asymmetrical basin at the west end of the section that is coincident and consistent with the basin imaged in the seismic record section. This hangingwall syncline model is a viable alternative tectonic interpretation of the north-south trending Fortymile Wash — Jackass Flats valley.

6 CONCLUSIONS

Preliminary interpretation of the AV-1 reflection line shows that substantial constraints on structural geometries can be gained by analyses and inspection of this type of data. Accordingly, our ability to develop and choose between alternative conceptual tectonic models may be significantly improved.

Preliminary conclusions, in order of confidence are:

- The presence of a major basin-bounding structure on trend with Fortymile Wash-Jackass Flats (Young et al., 1992) is supported.
- The structural style used to characterize Yucca Mountain by Young et al. (1992) is consistent with scoping interpretations of AV-1.
- Vertical and near-vertical shear is a valid deformation mechanism for the structural terrain in the Yucca Mountain region. A domino-style deformation mechanism is not supported.
- A detachment elevation of -5 km to -6 km as determined by Young et al. (1992) is supported by the geometry of the major half-graben imaged on line AV-1.
- Multiple detachment models should be examined further as a possible paradigm for fault geometries at Yucca Mountain.

7 RECOMMENDATIONS

There are two significant difficulties encountered in the interpretation of AV-1:

- Lack of good quality data below about 1—1.5 s twtt;
- Poor resolution of the available velocity data.

Both of these problems can be addressed by reprocessing of the reflection seismic data, and by combined geometric and seismic modeling. For example, using the conclusions of this report as a model base, synthetic imaging (e.g., ray-tracing methods) and interactive velocity analysis methods should be used to refine the velocity model in an attempt to improve the fidelity of depth conversion. Imaging of fault trajectories, and possible detachment surfaces may be improved by reprocessing of the prestack data with an improved velocity model. If available, the AV-1 data tapes will be acquired from the USGS. The feasibility of interactive velocity analyses and subsequent reprocessing will be determined by examining the pre-stack shot records and existing velocity analyses. If substantial improvements seem practical an activity will be added to the GS Task 3 work plan in Tectonics to develop methods for interactive geometric modeling and synthetic imaging of reflection seismic data.

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