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Style of Basin-Range Faulting as Inferred from Seismic Reflection Data in the Great Basin, Nevada and Utah

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ABSTRACT

A review of seismic reflection data from the Great Basin indicates three general modes of modern basin formation: (A) relatively simple asymmetric sags bounded by one or more major steep (~ 60°) planar normal faults, (B) tilted ramps associated with moderately to deeply penetrating listric normal faults, and (C) assemblages of complexly deformed subbasins associated with both listric and planar normal faults that sole into a gently dipping detachment surface. Faults of each mode are known to be active, as evidenced by historical, Holocene, or latest Pleistocene surface ruptures.

Reflection data from north-central Nevada indicate that many of the high temperature hot string systems in this area are situated along normal fault zones bounding basins of mode A. The concentration of geothermal activity in both north-central and northwestern Nevada coincides generally with a region of higher than normal heat flow for the province and a relatively high rate and density of Quaternary faulting and seismicity. These facts, together with the observation that most hot springs occur along range-front fault zones, have led to the popular interpretation that these hot-spring systems probably are largely the result of meteoric water circulating along the relatively steep fault zones to moderate depths (3-5 km) in the warm crust of the area.

In contrast, reflection data from central Utah and from the Raft River geothermal area in southwestern Idaho indicate that some of the geothermal systems in these regions are associated with basins and faulting of mode C, important components of which are low-angle (5°-35° dip) detachment faults at depths of less than 4 km. The transport of both geothermal water and magma across these detachment faults however, implies structural continuity between the upper and lower plates. Quaternary faulting is also prevalent in the central Utah geothermal systems; however, in contrast to central Nevada, many of the Utah geothermal areas (excluding the Raft River area) are related to young volcanic features.

INTRODUCTION

Geologic studies, particularly in the last ten years, have emphasized a long period of extensional tectonism during the Cenozoic throughout the Basin and Range province of the western United States. Basin-range faulting, the deformation responsible for the distinctive modern physiography of much of the Great Basin portion of the province, probably represents a unique late-stage event in this long history of extension. Major normal fault zones, commonly 50-80 km in length, bound the north-northwest to north-northeast trending modern range blocks. Their orientation, geometry, spacing, and depth of penetration are the chief factors that control the structural fabric of the region. Gravity and seismic reflection data suggest that the bedrock structure of the intervening sediment-filled basins may be graben-like (bounded on both sides by major normal fault zones) or half-graben-like (bounded on only one margin by a major "master" fault zone) or some variation between these two end-members.

In this paper we review the current status of our understanding of the geometry, mechanics, and history of major basin-range normal fault zones as these faults are known to exert a major control on geothermal systems. Topics covered include fault geometry, depth of penetration, proximity to magmatic systems or regional heat flow anomalies, and recency of movement. A description and discussion of the full range of the Cenozoic extensional tectonic styles as well as the timing of different events in the Great Basin region can be found elsewhere in this volume (Stewart, 1983).

MODES OF BASIN-RANGE FAULTING

Various modes of formation of the modern basins and ranges in the Great Basin have been proposed and reviewed extensively in the literature (cf., Stewart, 1971, 1978; Anderson and others, 1983). While they serve as useful end members representing failure in the brittle regime, we now know that basin-range structure is complex and probably includes a continuum of variation between the end member modes. Rather than describe the individual modes of formation in detail, we have chosen to emphasize the geologic and geophysical characteristics which distinguish each from the others. The primary variants in all modes are fault geometry and depth of penetration of faulting. Another important variant is the mechanics of lower crustal/upper mantle accomodation for the shallow extension and the nature of the coupling between that accomodation and the brittle upper crustal extension.

In a horst-graben model (Figure 1a) basins typically 10-20 km wide are bounded by approximately planar normal faults dipping about 60° basinward. A localized zone of extension must exist beneath the basin at depths of 8-17 km coinciding to the depth interval in which the planar graben faults intersect. Deep accomodation for extension may be by plastic flow, or by penetrative fracturing and subjacent penetrative shearing down to a detachment near the base of the seismogenic zone. Some localized extension beneath the basin may be accomodated by dike intrusion (Thompson, 1966). A major drawback of the horst and graben model is that it is difficult to accomodate the regional tilt patterns of both individual range blocks and sets of ranges (Stewart, 1971, 1978, and 1980), which is suggestive of a faulting style incorporating block tilting.

In its extreme, a tilted block mode with planar faults (Figure 1b) can result in domino-style extension with basins being created solely by the offset and down-tilting of the blocks adjacent to the master normal fault zone (e.g. Morton and Black, 1975). It is unlikely, however, that domino style extension will develop under conditions of widely spaced major normal fault zones such as in the Great Basin, where spacing of the fault zones (25-35 km), is approximately twice the depth penetration of faulting as determined by the depth of the seismogenic zone (10-15 km). The large ratio of fault spacing to fault depth requires enormous areas of cross-sectional accomodation between blocks in the tilted block/planar fault mode (Gross and Hillemeyer, 1982). To get around this space problem Stewart (1978, 1980) has suggested a model in which the large-scale tilted block structure actually is the buoyant response of blocks bounded by dipping faults and floating on a plastically extending substratum. Eaton (1982) objected to this model on the basis of the rheological properties of the crust in the Basin and Range province.

Probably a more realistic variation of the tilted block mode involves master curved faults that decrease in dip with depth (listric faults) (Figure 1c). Stratal downbending (reverse drag) and/or antithetic normal faulting toward such faults accentuate basin development adjacent to the fault zone. Rotation due to slip on listric faults can also help explain the observed tilts of the major blocks. In either the planar or listric fault variation of the tilted block model, basin development is influenced both by the spacing of the master fault zones as well as the depth penetration of faulting. Even without details of fault curvature, it can be argued geometrically, that basin width must be roughly proportional to the depth of penetration of the master normal fault zone. Clay models of extensional tectonism suggest that basin width is approximately twice the thickness of the faulted layer (e.g., Cloos, 1968, Figure 16, p. 429). The curvature of the fault surface and hence the long-enduring controversy regarding listric versus planar normal faulting proves to be of little importance, the critical criterion being the depth penetration of faulting.

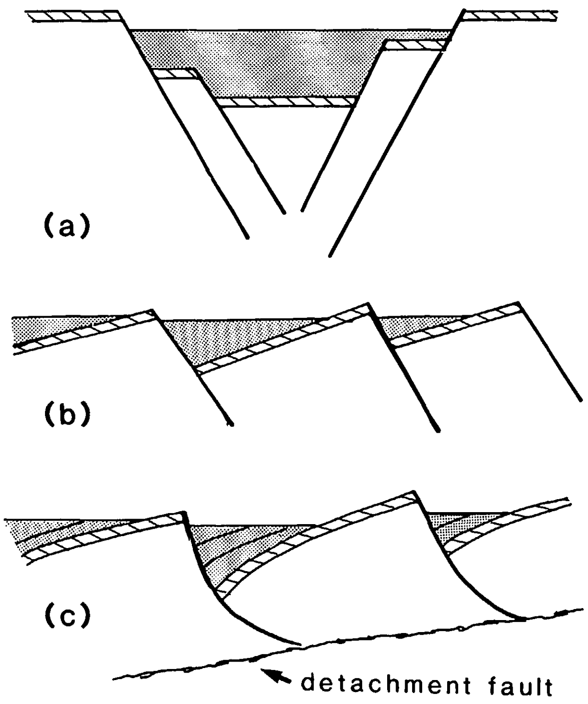


Figure 1. Proposed models of basin-range faulting. (a) Horst and graben; (b) tilted block/planar faults; (c) tilted block/listric faults.

Various models have been proposed to explain the relationship between upper crustal extension by faulting and lower crustal extension. Most models involve decoupling of the faulted part of the crust from the underlying crust on some sort of subhorizontal to gently dipping detachment fault or shear zone. Types of accomodation suggested for the crust beneath the gently dipping features include: none, for the special case where the feature penetrates the entire crust and possibly lithosphere (Wernicke, 1981); stretching and attenuation by steady state creep (Stewart, 1971, 1978; Eaton, 1982); and faulting and intrusive dilation (Cape and others, 1983; Miller and others, 1983). In all three cases lower crustal extension need not be directly beneath the loci of upper crustal extension; the largest horizontal offset between the two is associated with low-angle faults or shear zones that penetrate the entire crust and possibly lithosphere.

SEISMIC REFLECTION DATA

Publicly available and previously published seismic reflection profiles in the Great Basin provide a data base that is adequate for reviewing the large scale features related to basin-range faulting, particularly the basin shape and the continuity and patterns of dip of basin-fill strata. Anderson and others (1983) noted several limitations in using the available reflection data to directly study the subsurface fault geometry and the mode of deep accomodation of extension. First, the existing data are largely restricted to the upper few kilometers of crust (generally < 5 km). Second, it is not generally possible to accurately define the subsurface fault geometry with seismic reflection data for several reasons: (1) steeply dipping features (common surface dips of normal faults range between 40°-70°) generally are not recognizable as discrete reflectors with standard reflection processing even though sharp velocity contrasts may exist across them; (2) reflections from intrabasin strata adjacent to range-bounding faults (where they are most needed to resolve the detailed geometry of subsurface structures) are generally weak or absent probably because of the common presence there of coarse clastic wedges that are poorly sorted, poorly stratified, or chaotic; (3) reflections from pre-basin strata are generally of poor to very poor quality (largely due to extensive and complex pre-existing structure) and cannot be matched across major faults to obtain constraints on the geometry or magnitude of fault offset; (4) many of the existing profiles terminate at or short of the trace of the range-bounding faults. Low-angle detachment faults in the Great Basin, however, have proven to be prominent reflectors, due in part to their shallow dip (generally less than 15°) and also, to apparent high impedance contrasts associated with these fault zones (McDonald, 1976; Allmendinger and others, 1983).

To help get around these limitations, Anderson and others (1983) established several criteria based on features generally easily observed on the reflection data to distinguish between the various modes of faulting and basin development discussed earlier. These criteria include: overall basin geometry (symmetric or asymmetric), dip of basin-fill strata adjacent to major basin-bounding normal fault zones, and the pattern of basin sedimentation at basin margins. Anderson and others suggested three general modes of basin formation based on their analysis of available seismic reflection data: (A) relatively simple, commonly asymmetric, sags bounded on one or both sides by deeply penetrating relatively steep normal fault zones (either planar or gently listric); (B) tilted ramps associated with moderately to deeply penetrating listric normal faults; and (C) assemblages of complexly deformed subbasins associated with both listric and planar normal faults that sole into a gently dipping detachment surface.

Anderson and others (1983) discussed in detail all available seismic reflection data for the Great Basin as of the end of 1981. In this paper we summarize these data by giving examples of each of these three modes of basin formation. Some recently acquired seismic reflection data are also discussed. Figure 2 gives the location and source of all current publicly available seismic reflection data in the Great Basin together with the interpreted style of faulting keyed to the letter designations in the previous paragraph.

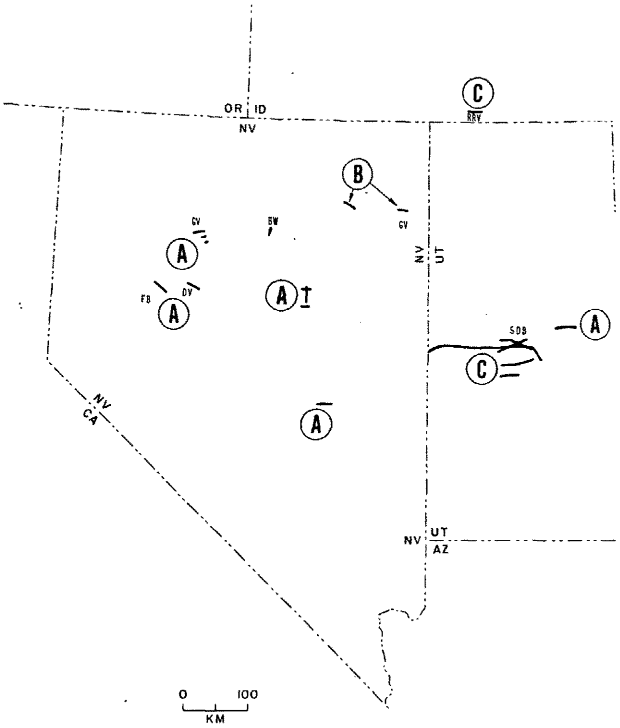


Figure 2. Available seismic reflection profiles in the Great Basin (heavy lines). Interpreted mode of basin structure indicated by letters (see text and Figure 14): (A) symmetric or assymmetric sag, (B) tilted ramp, (C) complexly deformed sub-basins. Place names indicated by small letters: FB-Fallon Basin, DV-Dixie Valley, GV (western Nevada) - Grass Valley, BW-Beowawe, GV (eastern Nevada)-Goshute Valley, SDB-Sevier Desert Basin, and RRV-Raft River Valley. References for Nevada seismic data are given in Anderson and others (1983) with the exception of Grass Valley, Nevada which is described in the text. Data in Utah are from COCORP (long E-W profile, Allmendinger and others, 1983), McDonald (1976), and Zoback (1982). Data in Raft River Valley, southwestern Idaho are from Covington (1983) and Ackermann (written communication, 1983).

Sag-like Basin Structure

The sag-like basin structure which is considered related to deeply-penetrating, approximately planar master normal faults is typified by the Fallon Basin area (Figure 2). Figure 3a shows an unmigrated, 22 km long, seismic reflection profile across the main part of the basin from Hastings (1979). Across most of the basin the sedimentary sequences (primarily lacustrine) are well-bedded and lack internal structural disruption as indicated by numerous continuous reflectors 10 km or more in lateral extent and a few that are more than 15 km in length. Many of these reflectors show a reversal of dip as they are traced from northwest to southeast and ultimately die out beneath the southeastern part of the basin (see migrated line drawing--Figure 3b). A broad asymmetric sag controlled by a steep planar normal fault is suggested as the predominant basin structure. Available data indicate that the Stillwater Range block, which is only 5-10 km wide and separates the Fallon basin on the west from Dixie Valley on the east, is bounded by structural basins that are approximate mirror images of one another (Anderson and others, 1983). Reflection data for Dixie Valley were described briefly by Anderson and others (1983) and are discussed in detail by Okaya and Thompson (1983). The latter authors combined analysis of the seismic reflection data with studies of the 1954 Fairview Peak (M = 7.2) earthquake to conclude that the major normal fault zone bounding Dixie Valley on the west is approximately planar and extends to a depth of about 15 km. Though the earthquake and reflection seismic data from the Dixie Valley area are consistent with a model that includes the "master" normal fault; it is instructive to consider an alternative model for formation of the asymmetric sag structure.

Figure 3c is a cross-sectional sketch of a clay model of extension done by R.K. Hose (written communication, 1983). The experimental design was similar to that described by Cloos (1968, p. 425) and was such that the faults terminate downward against overlapping tin sheets. The line of overlap between the two sheets remained fixed during the experiment and coincided with the furthest right hand faulting in the clay. Extensional traction was applied to the clay layer by sliding the underlying tin sheet to the left. If the top of the clay model corresponds to the base of a basin we see that it has the form of an asymmetric sag underlain by highly fractured material. Faults with major throw are not seen. Instead, the sag is produced by a combination of stratal attenuation and offset on many small faults. The stratal attenuation is probably accomplished by displacement on abundant unidentified microfractures and/or by grain-grain ajustments. Analagous attenuation of sub-basin rocks of the scale of Fallon basin (Fig. 3a) could be associated with displacements on a class of small fractures and faults with displacements ranging from a few centimeters to a few tens of meters. Such structures would be undetected by seismic reflection profiling even if good subbasin reflectors were present. Clearly, they could be extremely important to fracture, porosity, and premeability and hence to the potential for sub-basin water circulation. The absence of a master fault would not preclude strain accumulation sufficient to produce a large earthquake and associated extensive surface faulting. Some of the faults seen in the clay model, especially the sag-marginal ones, extend from the surface to the tin sheets. The overall width of the sag is nearly twice the depth to the tin sheets. If extrapolated to Fallon Basin or Dixie Valley these faults, though not of great displacement, would have a depth pentration of 9-10 km. The stress drop associated with a reasonable displacement of 3 m on such a fault could produce a large earthquake.

Tilted-Ramp Basin Structure

Anderson and others (1983) discuss two examples of tilted ramp basin structure from eastern Nevada. One of these, a profile published by Effimoff and Pinezich (1981) across Goshute Valley, extends from near the bedrock-alluvium contact on the east side of the Pequop Range eastward to a point several kilometers west of the base of the Toano Range (Figure 4a, for location see Figure 2). A line drawing of the data is shown in Figure 4b. In its eastern part the profile crosses a broad sediment covered pediment which is bounded on the west by a buried fault zone that appears to be the major structure controlling basin development. The overall gentle easterly tilt of the basin fill wedge as well as the dip of reflectors into the fault zone led Anderson and others to interpret this fault structure as a moderately deeply penetrating listric fault zone. This interpretation is at odds with that of Effimoff and Pinezich (1981) who suggest a sharply listric fault zone flattening only a few kilometers beneath the valley which is genetically related to a pre-existing thrust fault in the Toana Range.

The bedrock structure beneath the Goshute Valley may be very similar to the sketch of the clay model (model done by Cloos, 1968; sketch by Stewart, 1971) shown in Figure 4c. In this model the tilted ramp structure is largely the result of rotation related to slip on the master listric fault. Note however, that a distributed zone of antithetic faulting adjacent to the master fault zone tends to reduce the overall amount of tilting in the basin floor.

Another significant feature of the clay model shown in Figure 4c is the development of a cross-structure within the basin which is related to irregularities in the geometry of the master fault zone. This cross-fault is characterized by oblique slip (both horizontal and down dip components of motion). Possibly

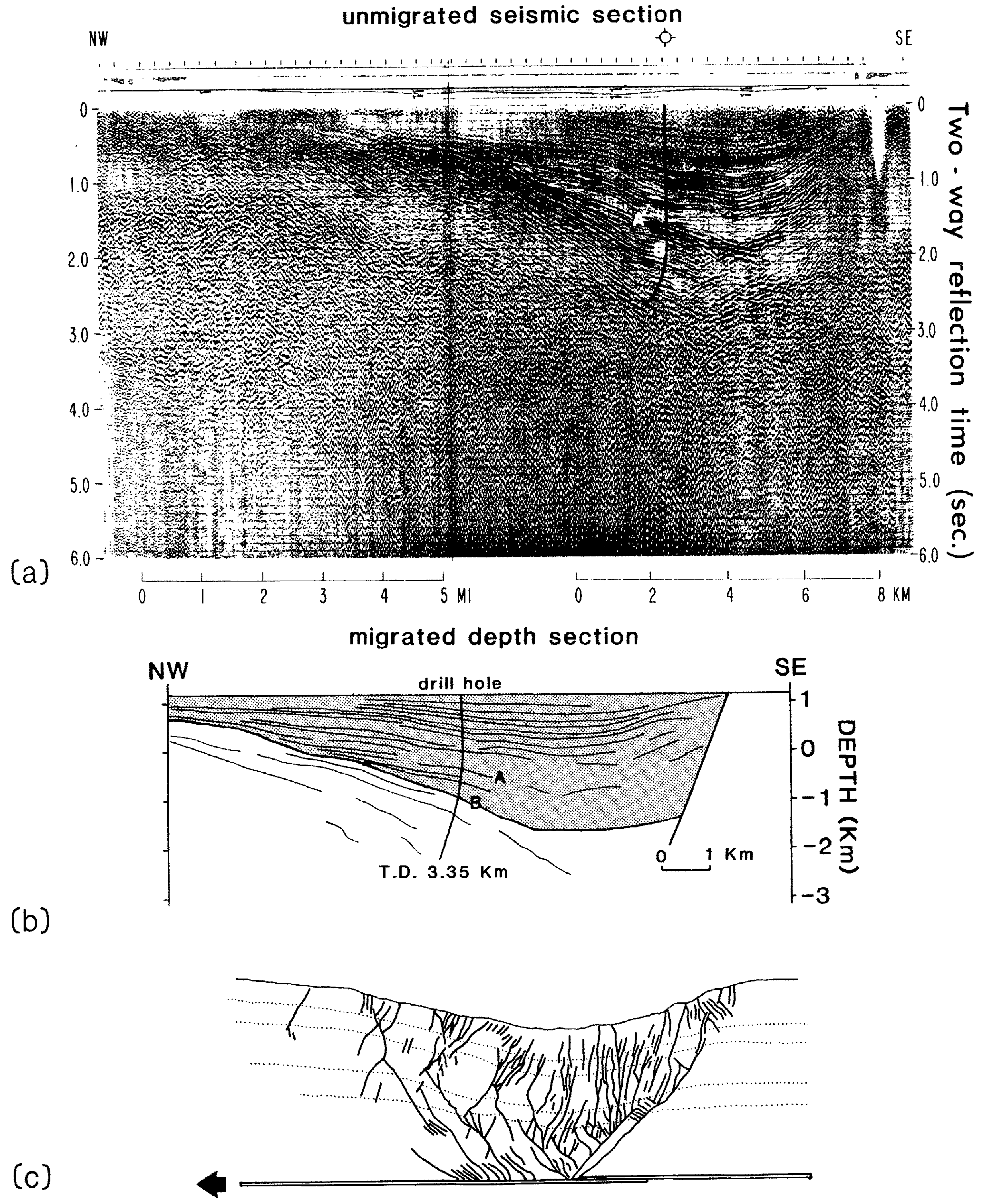


Figure 3. Sag-like basin structure. (a) Unmigrated seismic section across Fallon Basin, central Nevada (Hastings, 1979 and Anderson and others, 1983), (b) Line drawing of migrated depth section (Hastings, 1979 and Anderson and others, 1983), (c) Sketch of clay model of possible bedrock structure and faulting beneath the basin (clay model done by R. K. Hose, written communication, 1983; sketch by Stewart, 1971).

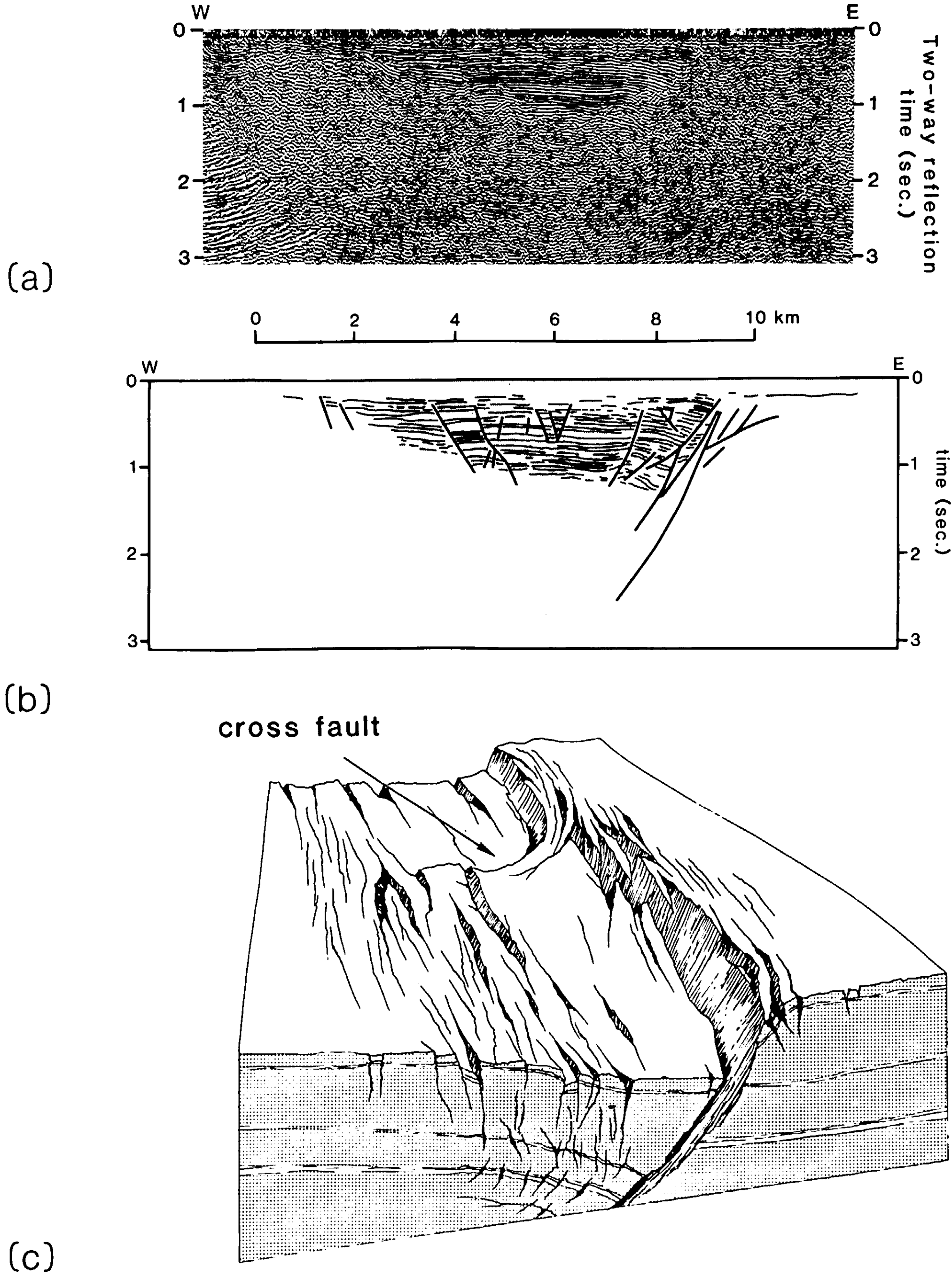


Figure 4. Basin above a tilted ramp structure. (a) Migrated seismic profile across Goshute Valley (Effimoff and Pinezich, 1981). (b) Line drawing of seismic profile with fault interpretation (Anderson and others, 1983). (c) Sketch (Stewart, 1971) of clay model by Cloos (1968) of possible bedrock structure and faulting beneath the basin.

analogous cross-strike zones of bedrock offset have been identified beneath numerous basins within the Great Basin by both seismic reflection (Effimoff and Pinezich, 1981) and gravity (c.f., Zoback, 1983) data.

Complexly deformed sub-basins above a shallow detachment fault

This style of basin development is typified in the shallow seismic reflection data in the Sevier Desert basin reported by McDonald (1976) and discussed in detail in Anderson and others (1983). The upper plate rocks in this area have been extended by numerous planar and listric normal faults. Major fault zones identified on the seismic reflection profiles have an average spacing of about 5 km. Dip components of sediments within the basin show a complex pattern of combined reverse and normal drag adjacent to these fault zones. The detachment fault itself, the Sevier Desert detachment, is apparent as a strong, relatively continuous reflector from the near surface to depths of 12-15 km (Allmendinger and others, 1983).

Another example of basin development above a shallow detachment fault comes from geological and geophysical studies and seismic reflection data from the Raft River geothermal area. Interpretation of a detailed seismic refraction study in the area indicate that there are no major normal fault offsets in the bedrock beneath the valley; however, faults with 50 m or less of vertical displacement could have been missed because of scatter in the data (Ackermann, 1979). A detachment fault has been interpreted to lie at the base of the Tertiary basin sediments along their contact with a thin sectin of Precambrian and lower Paleozoic metasedimentary rocks which mantle the crystalline basement (Mabey and others, 1978; Covington, 1980 and 1983). This interpretation is supported by an abrupt increase in fracturing near the base of the basin fill section that can readily be observed in drill core and also by low-angle normal faults in core sections obtained less than 200 m above the inferred detachment fault (Guth and others, 1981). This detachment fault is located at depths of less than 2 km beneath the valley in the vicinity of the geothermal area. Further eastward beneath the valley (downdip) the detachment fault has been interpreted as separating fault blocks of metamorphosed to nonmetamorphosed Paleozoic and Proterozoic rocks from the underlying basement complex at depths of 3 km or greater (Covington, 1983). Figure 5a shows a seismic reflection

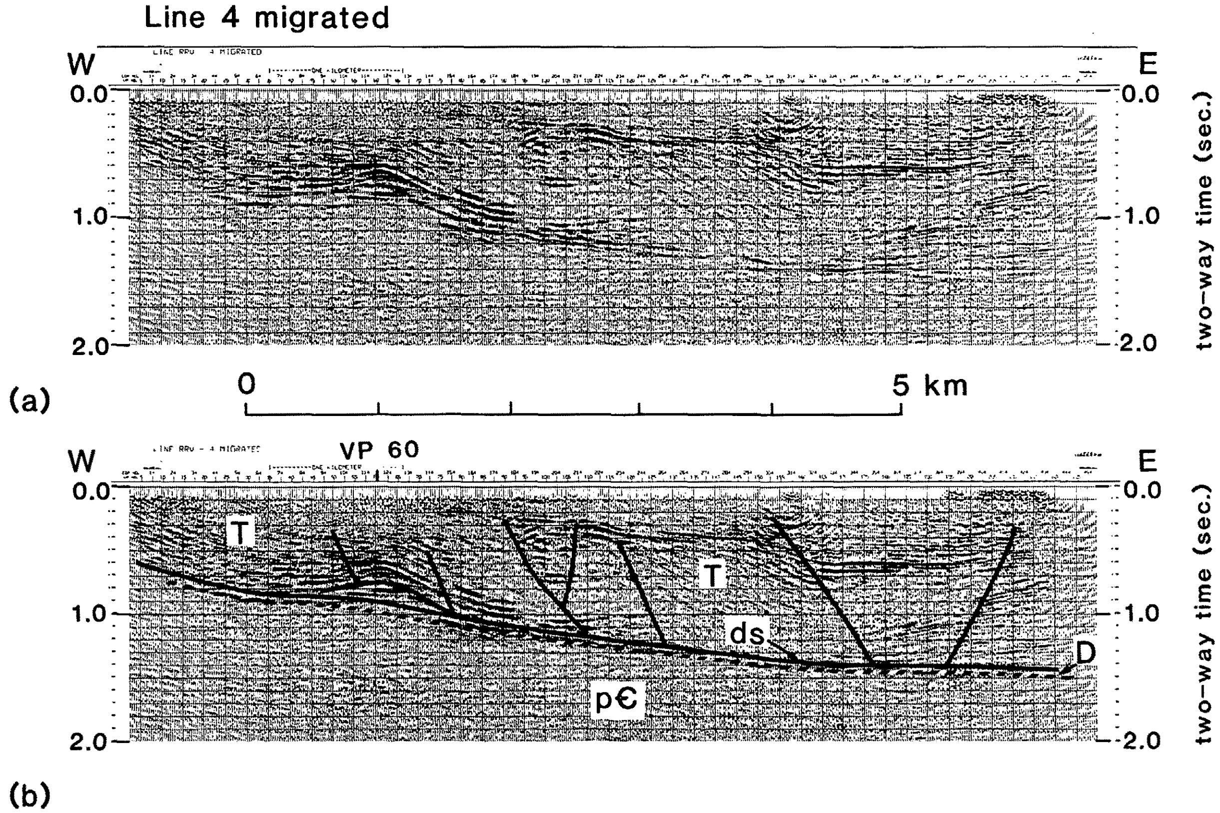


Figure 5. (a). Migrated seismic profile across a portion of Raft River Valley (H. D. Ackermann, 1983, written communication and Covington (1983). (b) Interpretation of Raft River profile showing major faults, modified from Covington (1983). Heavy dashed line indicates top of Precambrian crystaline basement (p Є), based on an integrated interpretatin of seismic reflection and refraction data (Ackermann, written communication, 1983). T, Tertiary basin sediments; ds, detachment surface; D, ductily deformed lower Paleozoic and Proterozoic schists and quartzites. Small antiform near VP 60 may represent a bedrock klippe above detachment fault.

profile across part of the valley in the vicinity of the geothermal area, an interpretation of the profile somewhat modified from that of Covington (1983) is given on Figure 5b. The inferred top of crystalline basement on Figure 5b comes from an integrated analysis of the seismic refraction and reflection data (H. D. Ackermann, 1983, written communication). Unlike the Sevier Desert detachment, the inferred Raft River detachment is not easily recognized as a prominent, nearly continuous reflector. However, as indicated on Figure 5b, several major normal faults within the basin fill do not appear to offset the top of crystalline basement or, by inference, the detachment fault in the metasedimentary rocks lying above the crystalline basement.

Of special significance in both the Raft River area and the Sevier Desert basin region is the general lack of evidence on the seismic profiles of breakage of the relatively shallow (< 4 km deep) detachment fault by the normal faults above it. However, as discussed more fully in the section on geothermal implications, there is ample evidence that both minor faulting and fluid motion must occur across the detachment surface in both areas.

Case Study: Grass Valley, Nevada

While the broad generalization and categorization of basin structure and fault geometry outlined above is appealing, detailed analysis of several closely spaced lines within a single basin commonly reveals many complexities. As an example, four seismic profiles in Grass Valley, Nevada, collected as part of the

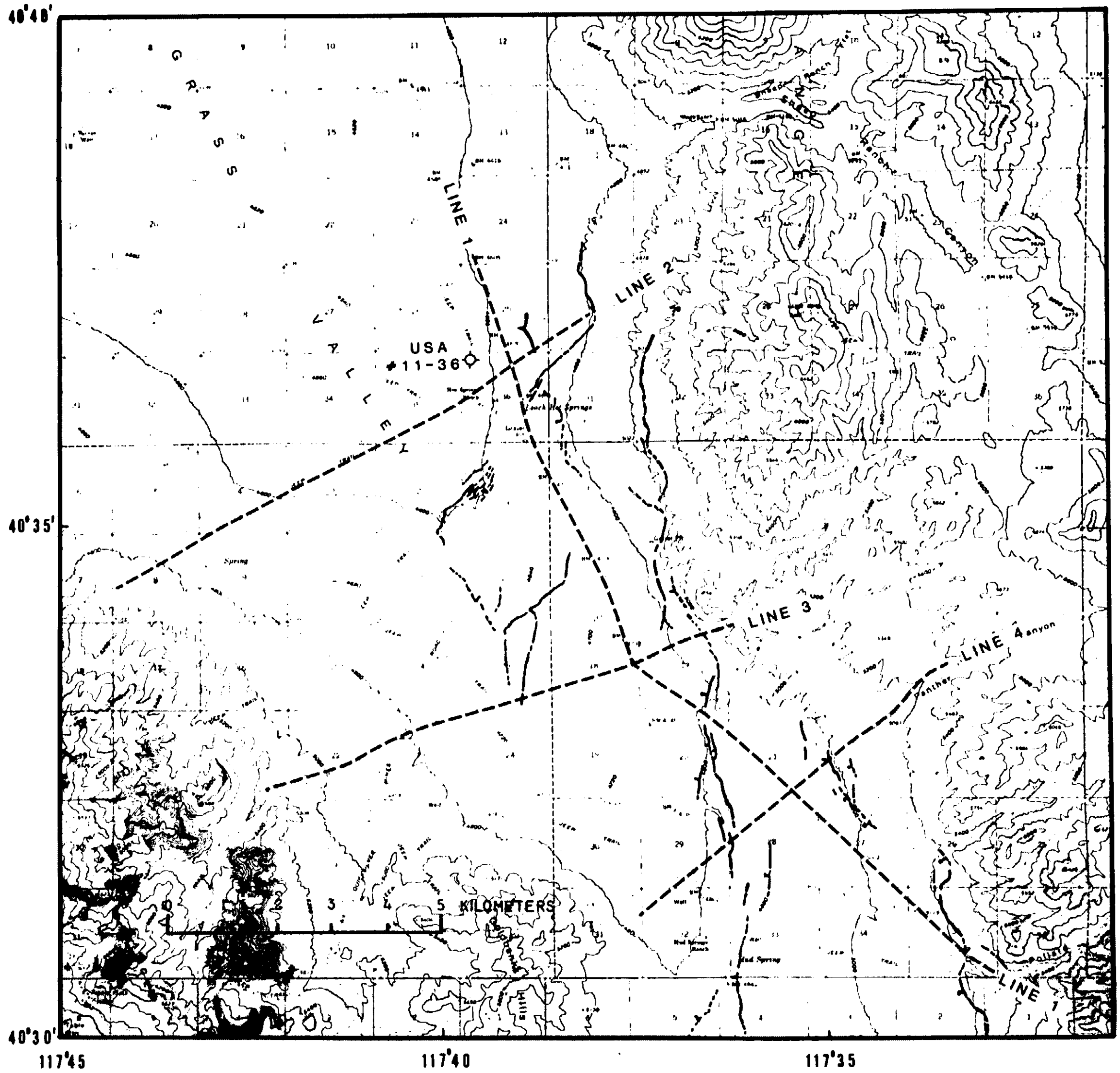


Figure 6. Map of Grass Valley, Nevada, showing Quaternary faults (heavy lines) from Wallace (1980b), locations of seismic reflection profiles (dashed lines), and well USA # 11-36.

Department of Energy/Division of Geothermal Energy (DOE/DGE) industry-coupled geothermal program, are discussed. Grass Valley lies between the Sonoma Range on the east and the East Range to the west (see Figure 2 for location). The valley is bounded on its east side by a major north-northwest-trending normal fault zone containing numerous Quaternary scarps including the faulting related to the 1915 M = 7.8 Pleasant Valley earthquake (Wallace, 1980a). Leach Hot Springs is located within this fault zone, near the intersection of a northeast-and northwest-trending fault.

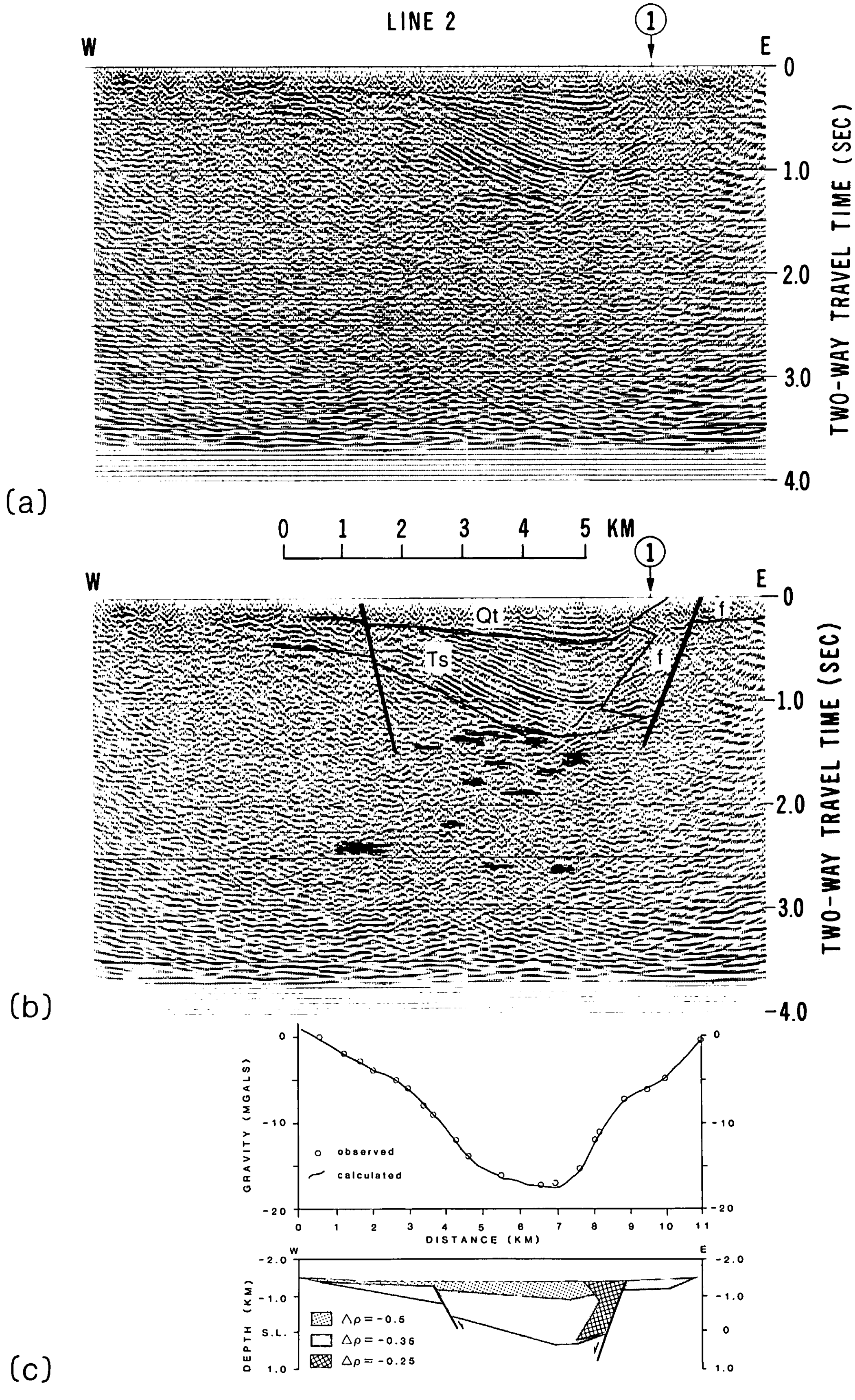
Three cross-valley vibroseis seismic reflection lines were run in Grass Valley along with one axial line, subparallel to the range front fault zone. The locations of the Quaternary fault scarps and the seismic lines are shown on Figure 6. The data were collected and processed by Sunoco Energy Development Company. A standard processing sequence was performed including deconvolution, velocity analysis, statics, stacking and filtering. Wave equation migration was also performed.

The overall basin structure of Grass Valley, as interpreted from the seismic reflection data, is asymmetric with a major normal fault zone on the east side and only minor faulting and/or downwarping on the western side. This overall asymmetry is consistent with the observed eastward tilt of the flanking range in this region (Stewart, 1980).

The asymmetric synclinal sag structure of the basin is most clearly demonstrated on Line 2 (Figure 7a) which begins at the base of a scarp in Quaternary-Tertiary gravels and fanglomerates along the base of the Sonoma Range, and extends westward across the valley and ends near an exposure of Cretaceous quartz monzonite in the East Range. Maximum basin fill thickness along Line 2 of about 1.7 km was determined from a combined analysis of gravity (Goldstein and Paulsson, 1978), well (USA #11-36, northwest corner section 36, T32N, R38E; Wilde and Koenig, 1980) and the seismic data. An interpretation of Line 2 is given in Figure 7b. A major west-dipping fault zone with an offset of ~ 1.2 km is interpreted to separate the basin from an alluvial covered pediment along the east margin of the valley. A smaller east-dipping fault zone occurs within the western half of the basin. The basin fill section is divided into two units based in part on an observed disconformity and also on seismic refraction data in the vicinity of the profile (Majer, 1978). A zone of relatively dense, probable alluvial fan material within the basin fill adjacent to the main fault zone was required to match the gravity data (Figure 7c). Other geometries shown in the gravity model in Figure 7c were interpreted from the reflection data. Also note on Figure 7b the highlighted series of subhorizontal reflectors in the bedrock beneath the basin between about 1.25 and 2.4 seconds depth. These are discussed below.

Line 3 begins in Paleozoic and Triassic sedimentary rocks, 0.5 km east of the main range fault zone. The final stack for Line 3 is shown in Figure 8a, the migrated version is shown on Figure 8b. Maximum fill thickness interpreted near VP 151 is about 1.0 km. The overall basin structure observed on Line 3 appears to be that of a tilted ramp; a prominent band of westward dipping reflectors in bedrock beneath the western edge of the basin (between about 1.25 to 2.4 seconds on the migrated section-Figure 8b) could be interpreted as a zone of a shallowly dipping normal faults or possibly the shallow portions of a series of listric faults. Apparent dip on these reflectors is between 24°-28°W. A tilted ramp basin structure would be consistent with a listric fault that flattened at such shallow depths (about 3 to 6 km). However, close inspection of the unmigrated section for Line 3 (Figure 8a) reveals an overlap of reflectors of opposing dip, a so called bow-tie structure, in the basin fill suggestive of a synclinal or sag structure bounded by a relatively steep, planar fault. On the unmigrated section the beds adjacent to the main fault zone are seen to dip basinward, not into the fault. Furthermore, this band of bedrock reflectors beneath the western edge of the basin occurs in approximately the same depth interval as subhorizontal reflectors (mentioned above) beneath the basin on Line 2, suggesting that they may correspond to a bedrock structure unrelated to the range-front fault. It is possible that the westerly-dipping reflectors beneath the basin on Line 3 may represent a faulted extension of near horizontal reflectors seen at about 0.70-0.75 seconds east of the main fault zone. These reflectors located east of the main fault zone as well as a number of shallower reflectors can be observed on the axial line, Line 1.

Line 4 crosses the narrowest part of Grass Valley, and begins in bedrock in the draw separating the Sonoma Range to the north from the Tobin Range further south (Figure 6). Line 4 lacks the characteristic well-defined reflections from the basin fill section (Figure 9). The gravity data (Goldstein and Paulsson, 1979) indicate that a transverse bedrock high, approximately coincident with Line 4, separates the Grass Valley basin from the Pleasant Valley basin to the south. Thus, Line 4 may cross a part of the valley where the basin fill is a thin veneer resting, at shallow depths, on complexly faulted bedrock. The only major reflector seen on Line 4 is a shallow west-dipping feature on the east end of the line. This surface is located east of most of the mapped Quaternary fault scarps transected by the line. The apparent dip of this reflector is between 17°-20°. It is located approximately 0.25-0.5 km below the fan surface. An updip projection of this surface suggests that it may coincide with the buried extension of the range and may possibly represent a buried pediment on bedrock. This basinward dipping surface is located near a left stepping en-echelon offset in the range front. However, the main zone of Quarternary faulting is located about 1.4 km basinward of the western, downdip truncation of the reflectors. Some minor Quarternary scarps do occur near the truncation of the reflectors.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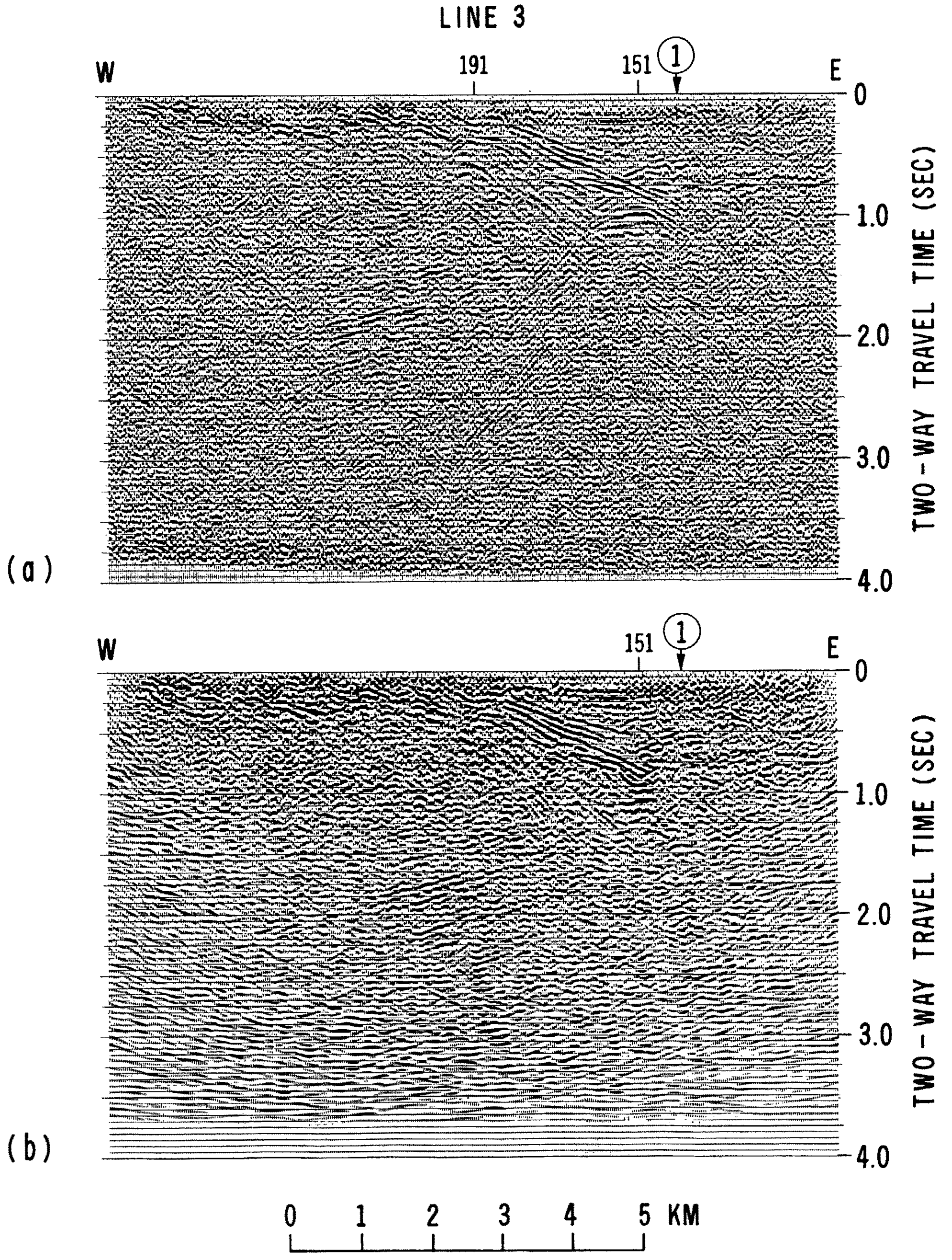
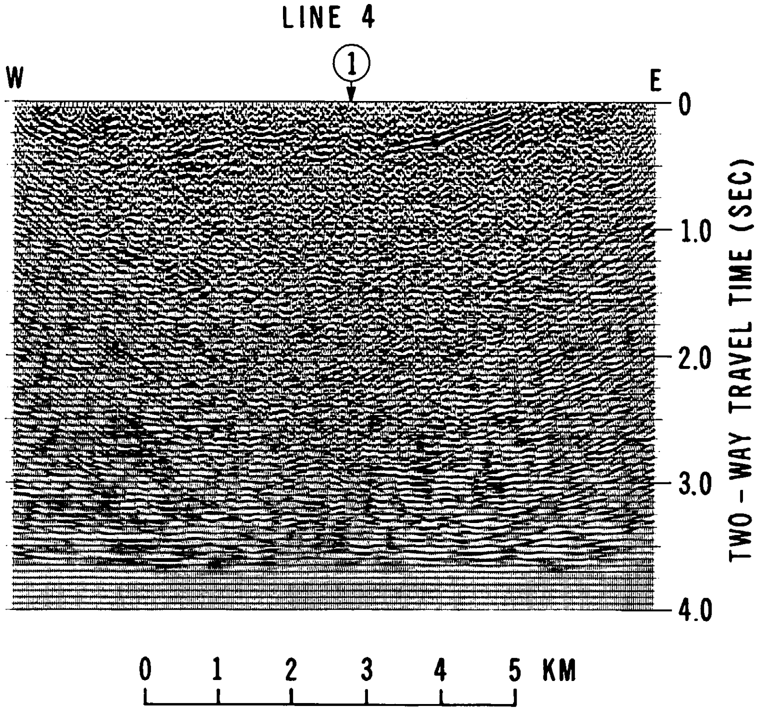


Figure 8. (a) Final stack for Line 3, Grass Valley. Circled number on top of section indicates location of cross line. (b) Migrated time section for Line 3.

Figure 7. (a) Migrated time section of Line 2, Grass Valley. Circled number on top of section indicates location of cross line. (b) Interpretation of Line 2. Qt, young basin fill; Ts, older basin fill, probably includes interstratified volcanic rocks; f, fan and pediment material. See text for further discussion. (c) Gravity model for Line 2, density contrasts (in g/cm^3)are indicated . Bodies just west of main fault zone are thought to represent fan material, somewhat denser than the rest of the basin fill section.

Figure 9. Migrated time section for Line 4, Grass Valley. Circled number on top of section indicates location of cross line.



Line 1 begins 2.75 km northwest of Leach Hot Springs and runs parallel to the axis of the valley (Figure 6). The reflection pattern observed on Line 1 is quite complex (Figure 10). Reflectors are difficult to interpret even in the vicinity of the cross valley tie lines. At the northernmost end of the line a section of basin fill sediments appear to have been crossed obliquely, however, for the most part the line runs along the steep gravity gradient associated with the major westward-dipping range-bounding fault zone. The high-amplitude sub-horizontal reflectors located in the upper 1.0 second, particularly in the southern half of the section, may represent fault zone reflections parallel to strike. A rather steep northward-dipping reflection observed near the intersection with Line 2 may represent a reflection off the northeast-striking, northwest-dipping fault that terminates near Leach Hot Springs.

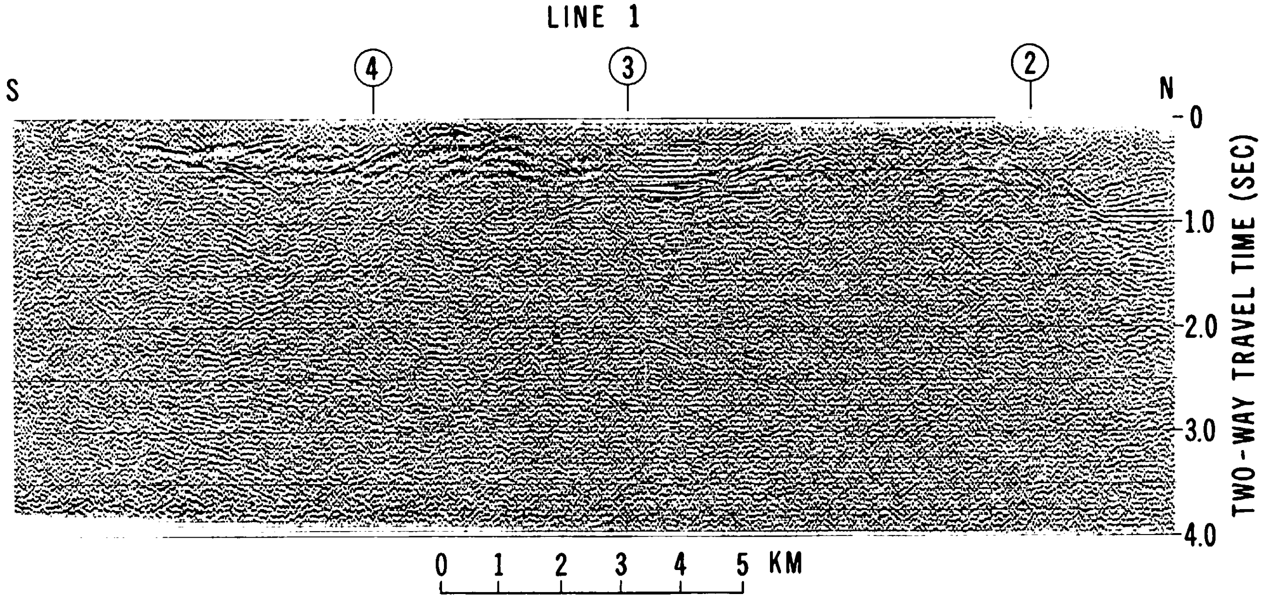


Figure 10. Migrated time section for Line 1, Grass Valley. Circled number on top of section indicates location of cross line.

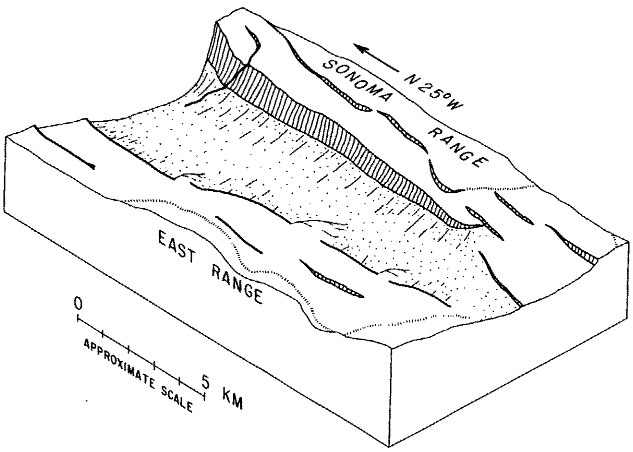


Figure 11. Generalized block diagram of bedrock structure beneath part of Grass Valley inferred from gravity and seismic reflection data.

In summary, the detailed seismic reflection coverage in Grass Valley indicate complex internal structure (Figure 11). The overall structure in the deeper parts of the valley (seen most clearly on Line 2) appears to be that of an asymmetrical sag. The major fault zone lies on the east side of the basin although there does appear to be minor faulting on the west side of the basin. Gently westward dipping sub-basin reflectors on Line 3, if viewed independent of the other lines, could be interpreted as reflections off a series of low angle faults. Based on similar, but horizontal, reflections seen in the bedrock beneath the basin on Line 2, these reflectors are thought to originate in bedrock structures unrelated to the main range front fault. A relatively steep, planar west-dipping fault zone decreasing in displacement to the south toward Line 4 is the favored interpretation of the master fault bounding the basin.

ADDITIONAL GEOPHYSICAL CONSTRAINTS ON THE SYTLE OF BASIN-RANGE FAULTING

Seismicity studies provide information on currently active brittle deformation in the upper crust. Several regional characteristics of extensional deformation in the Great Basin have emerged as a result of such studies: (1) brittle deformation is largely limited to the upper 15 km of crust; a summary of earthquake focal depths by Eaton (1980) indicated that about 80% of the events occur at depths of 10 km or less, (2) focal mechanisms indicate that slip is occurring on relatively high angle planes ($\geq$ 30°; c.f., Arabasz 1981; Vetter and Ryall, 1983 and Zoback, 1983), slip on the low-angle fault planes such as the Sevier Desert detachment may be largely aseismic (Smith, 1981), (3) in both regional and detailed local earthquake studies there is generally a very poor correlation between earthquake hypocenters and the likely downward projection of mapped surface faults (c.f., Arabasz and others, 1980 and 1981). This third point, together with studies of fault scarps formed in the M = 7.8, 1915 Pleasant Valley earthquake, lead Wallace (1979, 1980b), to suggest that upper crustal extension may in large part be controlled by localized deep zones of extension not necessarily related to the surface pattern of Basin and Range blocks. Some of the microseismicity may also be related to minor intrablock deformation.

Smith (1983) recently presented seismic reflection profiles across several segments of the Wasatch fault zone. The data were interpreted as indicating that some of the main basin-bounding faults along the Wasatch fault zone are sharply listric, becoming horizontal at depths of only 3-4 km. Earthquake focal depth studies in a 100 km wide zone centered along the Wasatch fault zone indicate that most events occur at depths of less than 10 km; however, 63% of the events occurred at depths greater than 4 km below the surface (Arabasz and others, 1980). Most of the events however, cannot be placed directly on the Wasatch fault zone. Many occur near the intersection of the Wasatch fault and transverse structural zones that often delimit distinct structural basins along the Wasatch fault (Zoback, 1983). An analysis of nodal plane dips for the larger of these events indicate slip on high-angle planes ($\geq$ 30°, with mean and median values of 49°-54°; Zoback, 1983).

Cape and others (1983) proposed a model to explain the disparity between earthquake focal depth studies and the shallow fault structure determined from seismic reflection data. Their model (Figure 12) involves two tiers of faulting within the upper crust, above and below a major detachment fault at a depth of 4-5 km, interpreted on the COCORP Rio Grande rift profile. This detachment fault was inferred, on the basis of seismic reflection and gravity data, to occur near the top of the Precambrian crystalline basement. This tiered fault model has faulting and intrusion in the layer beneath the detachment and may explain the broad focal depth distribution (generally 0-15 km) in areas where shallow detachments have been recognized.

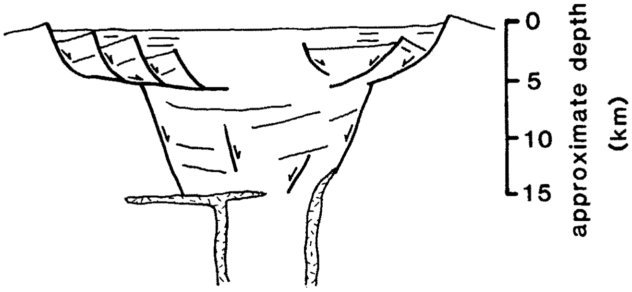


Figure 12. Proposed crustal model for extension in the Rio Grande Rift. Note deep intrusion and normal faulting above and below a shallow (< 5 km) detachment fault (from Cape and others, 1983).

GEOTHERMAL IMPLICATIONS

The seismic reflection data indicate the presence in some areas of the northern Basin and Range Province of predominantly planar and listric master basin-bounding faults that penetrate to depths of 8 to greater than 12 km in the upper crust. The commonly observed asymmetry in overall basin cross-sectional geometry as well as the regional pattern of tilted range blocks (Stewart, 1980) indicates that many basins are bounded only on one side by a deeply-penetrating master fault system. These master faults are clearly a critical component of geothermal convective systems in the Great Basin region as evidenced by the common occurrence of most modern geothermal systems along range-bounding fault zones. The basin margin bounded by the master fault zone can generally be predicted from the overall tilt of the surrounding ranges.

Cross-fault structures beneath the basins (as shown in Figure 4b) may play an important role in localizing a geothermal system along a master fault zone. Geothermal activity at Beowawe, north-central Nevada (see Figure 2 for location), may be largely controlled by cross-fault structures (Zoback, 1979).

A comparison of Quaternary fault scarps, surface heat flow, and the distribution of known geothermal systems with reservoir temperatures greater than 90°C (Figure 13) in the Great Basin indicates a direct correlation, attesting to the critical role that faulting plays in the development and maintenance of the geothermal systems particularly in regions of above average heat flow. Although the fault map does not represent uniform province-wide coverage, the general distribution pattern of faulting is probably correct. High levels of faulting occur in western Nevada and along a N-S belt in central Utah. These zones of dense Quaternary faulting compare well with the distribution of modern seismicity in the province (c.f., Smith 1978). In fact, seismicity and geologically-determined moment rates for these areas also compare quite well (Smith and Bauer, 1983). Thus, the observation that major geothermal areas tend to occur in zones of Quaternary faulting, (which are also seismically active today) suggest that the fault/fracture premeability, so important to the northern Basin and Range geothermal systems, is probably maintained by seismicity which counteracts the geochemical self-sealing nature of these systems.

The occurrence of geothermal systems with reservoir temperatures greater than 90°C is densest in western Nevada, especially for the hottest systems (reservoir temperatures >150°C). Significantly, many of the hottest geothermal systems occur within the regions of highest heat flow, particularly the Battle Mountain high region of northern Nevada (Sass and others, 1971; Sass and others, 1981) where heat flow values are approximately double the continental mean. The available seismic reflection data in this region suggest sag-like basins which we have interpreted as being bounded by relatively steep, deeply penetrating master fault zones. As mentioned above, the high level of seismicity and Quaternary faulting in this area are probably a major contributing factor in the development and maintenance of fracture permeability allowing the deep circulation of meteoric water in these systems. There remains a serious problem however with invoking conductive heating of deeply circulating meteoric water as the primary heat source for many of the long-lived Great Basin hot-water geothermal systems. It seems unlikely that fracture porosity could be great enough to supply enough heated surface area to maintain geothermal systems for several hundred thousand years. Zoback (1979) estimated an age of 200,000 years for the Beowawe, north-central Nevada geothermal system (See Figure 2 for location).

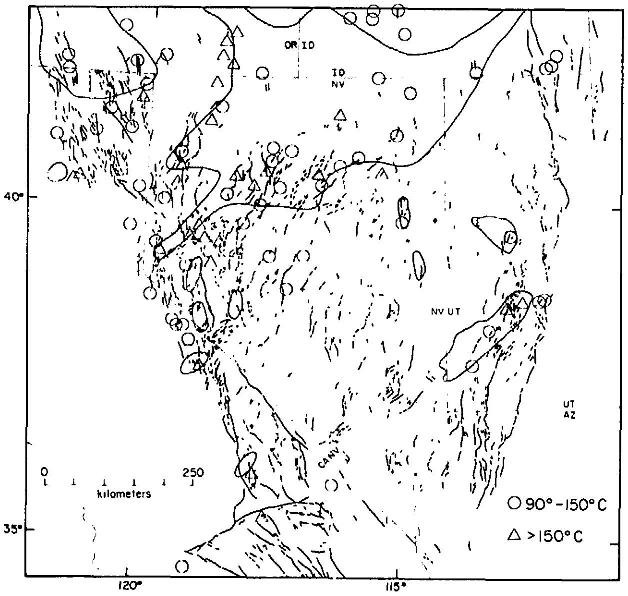


Figure 13. Geothermal systems with reservoir temperatures > 90°C (Muffler, 1979) superimposed on a map of Quaternary faulting in the Great Basin (Nakata and others, 1983) and regions of high heat flow (shaded regions heat flow ≥ 2.5 HFU, 104 mW/M^2, Sass and others, 1981). Circles indicate systems with reservoir temperatures between 90°-150°C; triangles indicate systems with reservoir temperatures greater than 150°C.

The geothermal systems in the Black Rock Desert region of central Utah (Figure 13) are located in or near zones of late Quaternary basalt and rhyolite volcanism and Quaternary faulting. Strontium isotopes indicate that the basalts have a mantle source (Hoover, 1974). The zone of Quaternary faulting and volcanism in the Black Rock Desert lie along a buried major normal fault zone that can be inferred from gravity data (Figure 14). This localized zone of tectonism occurs above the Sevier Desert detachment fault in an area where the detachment is at a depth of less than 3 km (McDonald, 1976), and must represent a major break in the otherwise largely continuous detachment fault. The magmatic,

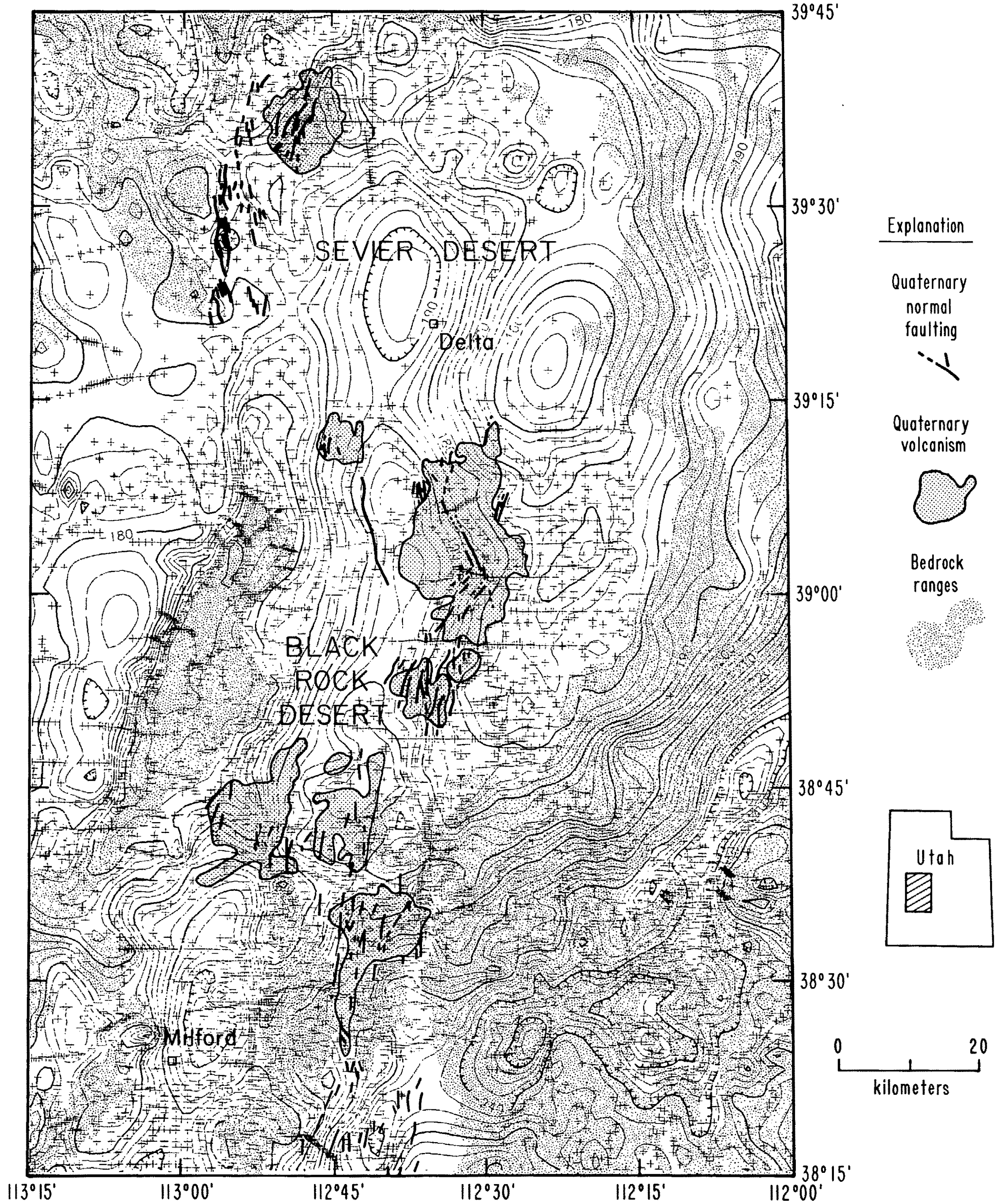


Figure 14. Complete Bouguer gravity map of the Black Rock Desert area of central Utah. The pronounced north-south gravity low near the center of the map indicates the presence of an intrabasin graben. The gradients on either side of the low define the graben-bounding fault zones. Sites of primary basaltic volcanism are patterned; Quaternary faults are approximately located by heavy lines, and gravity stations are indicated by crosses. Sources of gravity data are U. S. Geological Survey gravity files and Serpa and Cook (1980).

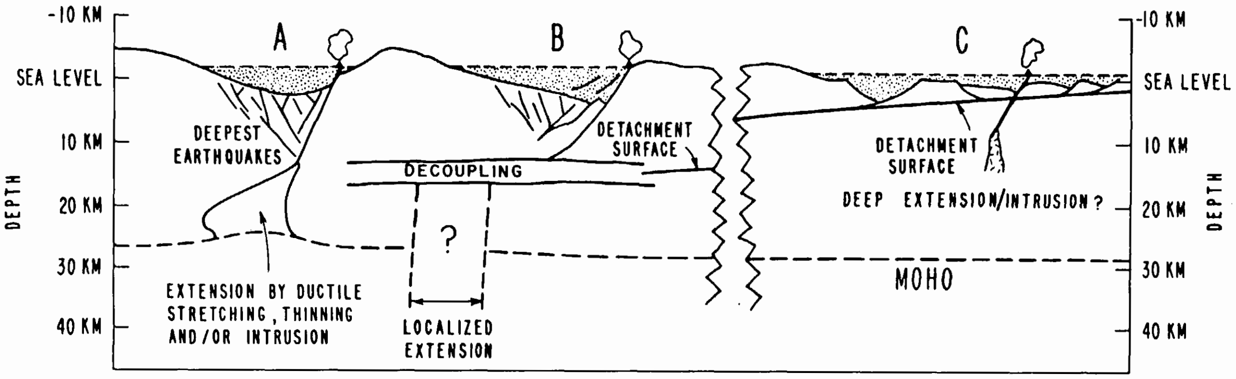


Figure 15. Diagramatic cross section showing three modes of basin formation and normal faulting that may exist in the Great Basin together with possible lower crustal styles of extension. Major structures related to geothermal systems are indicated. Stipple pattern indicates basin fill sediments. Modified from Anderson and others (1983).

geothermal, and faulting activity in this area are no doubt genetically linked. They probably indicate a localized zone of lower(?) crust extension which is largely unrelated to the overall pattern of extension tied to the Sevier Desert detachment.

Geophysical investigations (primarily seismic reflection profiling) have indicated shallow low-angle detachment faults in other geothermal areas. In the Roosevelt Hot Springs area, Utah (located less than 50 km southwest of the Black Rock Desert region) the geothermal reservoir is formed by a complex system of faults and joints in Precambrian and Tertiary crystalline rocks. A major component of this fracture system is a very shallow low-angle detachment fault (at a depth of less than one km, Bruhn and others, 1982). The ultimate source of heat for this system is believed to be an igneous intrusion related to young (less than about 0.6 myBP) rhyolitic volcanism (Ward and others, 1978; Robinson and Iyer, 1981).

Drilling has verified that the geothermal reservoir in the Raft River Valley is a highly fractured zone near the base of the Cenozoic basin fill (Mabey and others, 1978). Mabey and others (1978) speculated that the geothermal waters encountered in the reservoir were conductively heated by circulation to depths of 3 to 6 km. As the reservoir is located in the basin fill section, above the inferred detachment fault at the the base of basin fill at a depth less than 2 km, it appears that there must be major vertical flow of geothermal water across the detachment fault implying some sort of structural break across the detachment.

The style of deep accomodation for brittle, upper crust extension also has geothermal implications. Thermo-mechanical modelling of Lachenbruch and Sass (1978) demonstrated that the observed heat flux and extension rates in the Great Basin are consistent with either stretching or intrusive dilation of the lower crust. Localized intrusion beneath basins to accomodate extension produced by intersecting, approximately planar graben faults could provide a method of elevating geotherms to structural levels where they can be reached by circulating groundwater. Obviously, intrusion along the deeper portions of major basin-bounding faults, if common, could result in a significant geothermal potential at shallow depth throughout the region. The relatively small volumes of young (less than 6 my BP; cf. Stewart and Carlson, 1976) volcanism in the interior of the Great Basin have been cited as evidence against the widespread applicability of intrusion into basin-bounding faults. Anderson and others (1983) presented additional arguments suggesting that while intrusion beneath basins may exist locally, it probably isn't a province-wide phenomena.

SUMMARY

On the basis of available seismic reflection data, three main modes of normal faulting and basin development can be defined for the Great Basin region. Figure 15 summarizes basin structure and fault style for each mode along with salient features possibly related to geothermal potential. Lower crustal styles of extension are also shown. Faults in basins formed by each mode are known to be active as evidenced by historic, Holocene or latest Pleistocene surface rupture (Anderson and others, 1983).

Potentially the most important geothermal resource type in the Great Basin province is a convective system in which cold meteoric water decends along faults and fractures in an area of high thermal gradient, is heated, and convects upward through other faults and fractures. From the viewpoint of resource potential, it is critical to identify the master fault zones, which penetrate deeply and control circulation. The distributed zones of synthetic and antithetic minor faulting shown in modes A and B probably only modify or complicate the picture. The close association in western Nevada of belts of major geothermal systems, high heat flow, dense Quaternary faulting, and seismicity indicate the critical role that active faulting and fracturing play in the development and maintenance of convective geothermal systems. Quaternary faulting is also prevalent in the central Utah geothermal systems; however, in contrast to western Nevada, most of the Utah geothermal areas are related to late Quaternary volcanic features.

Low-angle normal faults (detachment faults) and fractures related to these faults are important structural features of many of the Utah geothermal areas. Both geothermal water and magma transport across these shallowly- dipping detachments imply some structural continuity between the upper and lower plates. The detachment faults do not appear to act as any sort of seal for the geothermal systems and must be broken in places. The possible role of detachment faults in providing significant lateral permeability remains to be investigated.

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Large size paper copies of the Grass Valley seismic reflection data are available (for a minor reproduction charge) through the University of Utah Research Institute, 420 Chipeta Way, Salt Lake City, Utah, file number NV/LCH/AMN-6.

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