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History of Cenozoic Extension in Central Sevier Desert, West-Central Utah, From COCORP Seismic Reflection Data[1]

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ABSTRACT

COCORP seismic reflection data show that Cenozoic extension beneath the Sevier Desert has had movement along a major, west-dipping surface. Reflections were obtained from several stratigraphic zones of known age within the Sevier Desert basin. The geometric relationships of these zones indicate that extension has occurred in at least two stages. A large first stage of movement (20-30 km or 12-18 mi) began after the middle Oligocene (26-28 Ma) and continued into the Miocene. This activity was followed by a probably short period of quiescence and erosion. A later episode of movement of smaller proportions (< 8 km or < 5 mi) began during or after the eruption of a middle Pliocene (4.2 Ma) basalt. This later stage is still active, as indicated by fault scarps which offset recent sediments in the basin. The record of extension within the Sevier Desert reflects the history of movement along the underlying Sevier Desert detachment, a major, low-angle normal fault that has been traced over 70 km (43 mi) perpendicular to strike and to depths of 12-15 km (7.5-9.3 mi). The record of displacement along the Sevier Desert detachment may have implications for the general history of extension in the Basin and Range Province.

INTRODUCTION

Extension has occurred within large regions of the western United States since the Oligocene. Two different types of interactions have occurred along the western margin of the North American plate: (1) the waning phases of subduction of the Farallon Plate, and (2) the formation of the San Andreas transform system (Atwater, 1970; Coney, 1978). The recognition of mid-Tertiary low-angle extensional detachments in the Great basin has raised the question of whether there are two distinct phases and styles of Tertiary extension or a continuum. Do the detachments and related ignimbrite volcanism represent back-arc spreading fundamentally different from the high-angle, fault-bounded mountain blocks that characterize the current Basin and Range morphology (Zoback et al, 1981), or has extension been essentially continuous and of the same style during the middle and late Tertiary, regardless of changing plate-margin interactions (Wernicke, 1981)? One way to approach this question is by analyzing in detail the evolution of Tertiary sedimentary basins and their controlling structures.

One of the largest basins in the eastern Basin and Range, the Sevier Desert basin, was recently the site of a seismic survey conducted by the Consortium for Continental Reflection Profiling (COCORP). The displacement, faulting, and tilting of the sedimentary and volcanic rocks in the basin reflect the middle and late Cenozoic history of extension along the underlying Sevier Desert detachment. This detachment is a low-angle, west-dipping feature that has been traced over 70 km (43 mi) perpendicular to strike and to depths of 12-15 km (7.5-9.3 mi) (Allmendinger et al, 1983). The rocks within the basin are cut by high-angle normal faults which either sole into or are truncated by the detachment, thus documenting extension along the detachment itself. Minor displacements of the detachment surface (much less than 500 m or 1,600 ft) along high-angle normal faults are possible because marked lateral velocity variations produce velocity pull-downs that cannot be distinguished from real structure (Peddy et al, in press). However, most of the vertical structural relief represented by the Cenozoic basin can only be accounted for by horizontal displacements on the detachment, not by movements on high-angle normal faults.

The COCORP seismic lines indicate the presence of a widespread angular unconformity within the basin. On the west side of the basin, this unconformity separates moderately east-dipping (18°-25°) Oligocene fluvio-lacustrine sedimentary rocks and synorogenic conglomerates of presumed Miocene age from middle Pliocene basalt flows and younger fill that dip gently eastward (1°-3°). The moderately dipping, middle Tertiary sedimentary rocks record an early episode of large displacement and tilting that began after the middle Oligocene (26-28 Ma), and lasted into the Miocene. This episode was followed by a probably short period of quiescence, during which erosion truncated the tilted middle Tertiary sedimentary strata. A later stage of movement of smaller magnitude has occurred since the middle Pliocene and continues to the present, as indicated by fault scarps which offset recent sediments in the basin (Bucknam and Anderson, 1979; Zoback, 1983; Crone and Harding, 1984). Despite the evidence for two periods of displacement on the detachment, there is no resolvable difference in the rate of extension during those two times.

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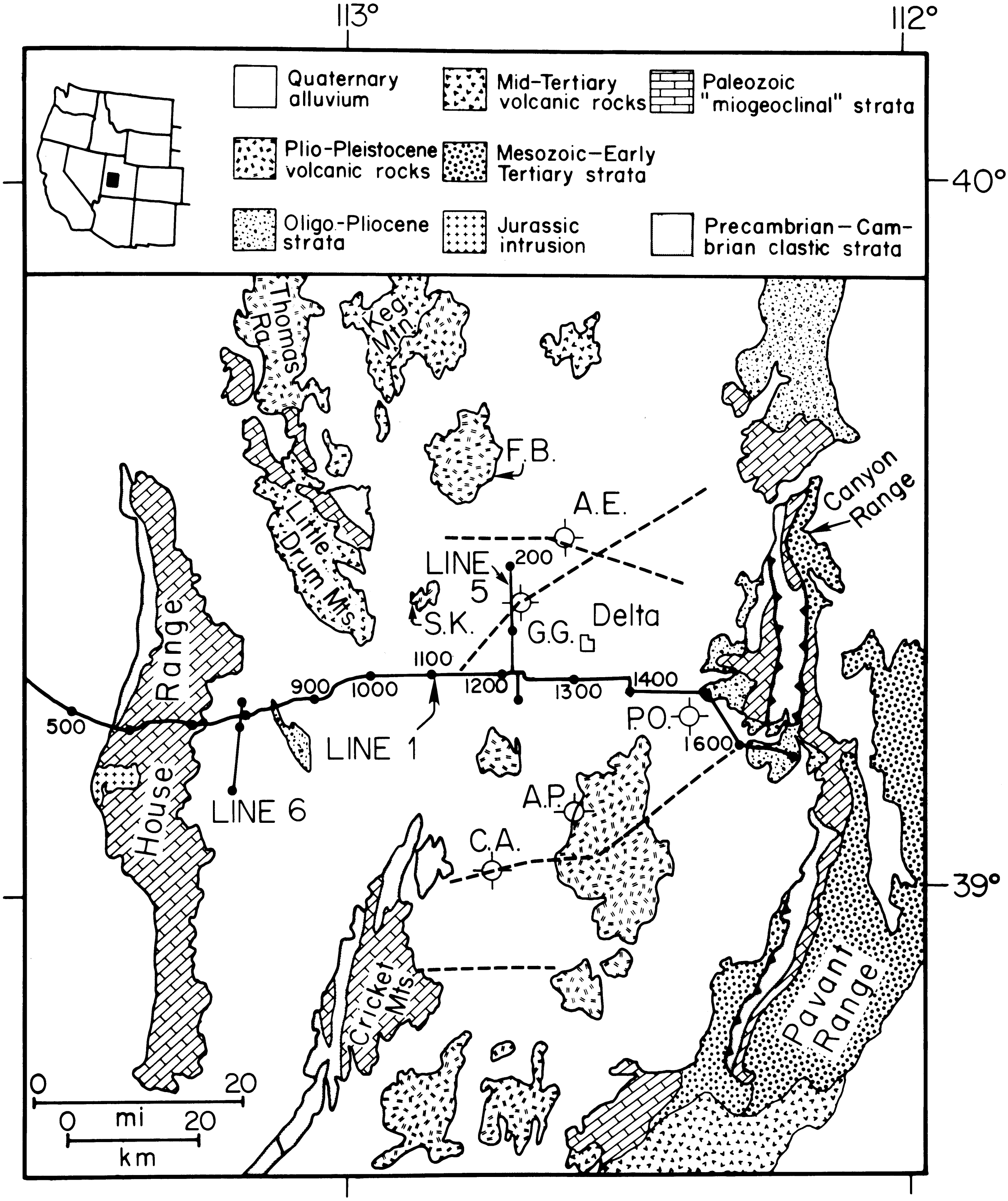


Figure 1—Sevier Desert location map. Geology of surrounding areas generalized from Hintze (1980). Dashed lines are locations of seismic sections published in McDonald (1976). S.K. = Smelter Knolls; F.B. = Fumarole Butte; G.G. = Gulf 1 Gronning; A.E. = Argonaut Energy 1; P.O. = Placid Oil 1 Henley; A.P. = ARCO Oil and Gas 1 Pavant Butte; C.A. = Cominco American 2 Beaver River.

The COCORP seismic data are concentrated in the central portion of the Sevier Desert. It is possible that the northern and southern portions of the basin have somewhat different evolutionary histories than the central area. Previously published seismic lines (McDonald, 1976) do show some changes along strike within the basin. The term "Sevier Desert" used in this paper refers to the area exclusive of these northerly and southerly extremes, and of the Sevier Lake area between the Cricket Mountains and the House Range (Figure 1). Petroleum exploration in the eastern Basin and Range has been sporadic and generally restricted to tests of the potential of the Paleozoic miogeoclinal strata. In eastern Nevada, however, the Eagle Springs and Trap Springs oil fields have production from both Tertiary and upper Paleozoic strata. The COCORP data provide new insight into the role of low-angle extensional detachments in this structurally complex frontier area, and may help illuminate new types of subdetachment drilling targets.

TECTONIC AND REGIONAL SETTING

The Basin and Range Province is a vast, elevated region in the western Cordillera consisting of fault-bounded mountain blocks separated by basins filled with fluvial and lacustrine sedimentary strata, volcanic rocks of both intermediate and basaltic composition, and conglomeratic deposits shed off the adjacent ranges. The Sevier Desert basin is an extensional feature of middle to late Cenozoic age covering 7,500 km^2 (2,900 mi^2) of the eastern Basin and Range Province in west-central Utah (Figure 1). It is bounded on the west by the House Range and by the Canyon and Pavant Ranges on the east.

The uplifted mountain range blocks that encircle the Sevier Desert expose a wide variety of rock types and structural features. The Canyon and Pavant Ranges, east of the basin, expose Mesozoic thrust faults of the Sevier orogenic belt (Armstrong, 1968). These ranges are adjacent to the transition zone between the Basin and Range and Colorado Plateau Provinces. Basaltic cones and flows in the southern part of the Sevier Desert are a northern extension of the Quaternary Black Rock volcanic field (Condie and Barsky, 1972). The Cricket Mountains expose lower Paleozoic miogeoclinal sedimentary strata to the southwest of the Sevier Desert. The House Range, an east-dipping homocline, forms the western margin of the basin (Hintze, 1974, 1981a, b). The Tertiary sedimentary strata on the wide eastern dip slope of the House Range merge into the strata of the basin. Tertiary ash-flow tuffs and rhyolite flows unconformably overlie Paleozoic miogeoclinal rocks in the Thomas, Drum, Little Drum, and Keg Mountains north and northwest of the basin (Hintze, 1980; Lindsey, 1982).

The asymmetric Sevier Desert basin contains rocks that can be broadly grouped into five units: (1) Oligocene ash-flow tuffs and rhyolitic flows, found mainly on the western flank of the basin; (2) Oligocene and possibly Miocene fluvio-lacustrine deposits; (3) Miocene conglomeratic deposits derived from local source areas; (4) basalt flows and cones of Pliocene, Pleistocene, and Holocene age; and (5) Pleistocene deposits of glacial lake Bonneville covered in places by recent alluvium (Gilbert, 1890; McDonald, 1976; Clark, 1977; Mitchell, 1979; Lindsey et al, 1981; Lindsey, 1982). Additionally, significant evaporite bodies, probably of Oligocene age, have been mobilized in the basin (Lindsey et al, 1981).

CENOZOIC STRATA OF WEST-CENTRAL UTAH

Surface Data

The middle and late Cenozoic strata of west-central Utah are exposed only locally and in incomplete succession (Heylmun, 1965). However, these outcrops are important because they represent, in part, the concealed stratigraphy of the Sevier Desert basin.

Oligocene-Miocene.—The House Range has outcrops of conglomeratic deposits of varying thicknesses, interbedded with Oligocene tuffs (Figure 2) (Hintze, 1974, 1981a, b). These rocks unconformably overlie Upper Cambrian carbonate strata. One of the tuffs has been identified as the widespread Needles Range Formation (Hintze, 1974), which has an age of about 30 Ma (Armstrong, 1970). Isolated outcrops of Oligocene lacustrine limestone are also present.

In the Thomas and northern Drum Mountains on the northwest side of the Sevier Desert, thick sequences of Miocene to Eocene rhyolitic flows and ash-flow tuffs rest with angular unconformity on Devonian to Precambrian strata (Figure 2) (Lindsey, 1982). A composite thickness of these units based on discontinuous exposure is more than 2,000 m (6,600 ft). Within the 42-21 Ma volcanic sequence are several unconformities, which Lindsey (1982) relates largely to volcanic cauldron collapse and erosion. However, a prominent angular unconformity between the Spor Mountain formation (21.3 Ma) and the Topaz Mountain Rhyolite (~ 6.3 Ma) probably marks the onset of extensional tectonism in the region (Lindsey, 1982). This unconformity is approximately the same age as a prominent angular unconformity seen on the COCORP data.

The Canyon Range has some of the thickest exposures of middle to upper Tertiary sedimentary rocks in the Sevier Desert area (Figure 2). These poorly dated strata total perhaps 1,700 m (5,600 ft) in thickness and unconformably overlie more than 4,800 m (15,700 ft) of Upper Cretaceous-Paleocene synorogenic conglomerate and sandstone derived from the Sevier orogenic highland. The Oligocene(?) Fool Creek Conglomerate was interpreted by Campbell (1979) to be a pre-Basin and Range deposit that filled in the preexisting topography. Based on lithology and morphologic relations (but lacking absolute or relative age constraints), the undated Fool Creek Conglomerate has been correlated with a unit about 65 km (40 mi) to the north that is overlain by a 32 Ma quartz latite (Campbell, 1979). The Miocene Oak City formation is separated from these rocks by an erosional unconformity. This younger formation is composed of a series of interbedded conglomerate, sandstone, and siltstone that were deposited in response to the Miocene uplift and westward tilt of the Canyon Range. The Oak City formation probably correlates with conglomeratic deposits encountered in the Gulf 1 Gronning well.

Pliocene-Pleistocene.—Numerous upper Cenozoic basaltic flows, cinder cones, and lesser amounts of intermediate composition volcanic rocks are present in the Sevier

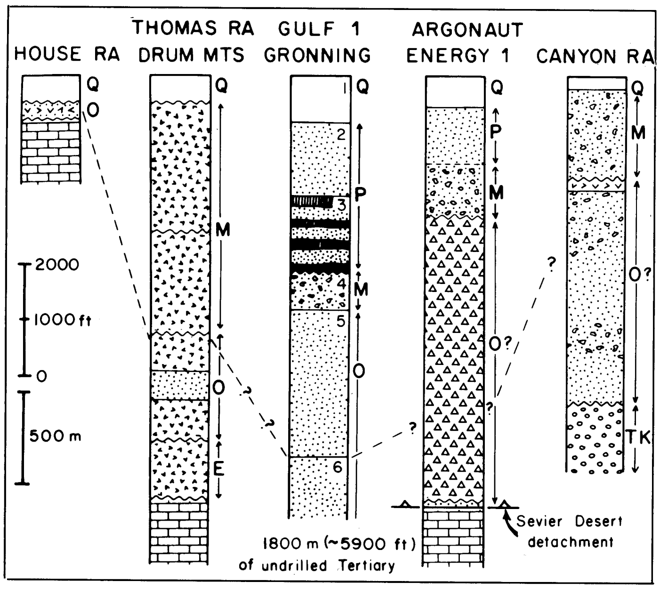


Figure 2—Stratigraphic sections from west-central Utah. Patterns same as for Figure 1, and pattern of Oligocene rocks in Argonaut well represents halite. Unit 3 in Gronning well is interbedded basalt flows and sediments. Angular unconformities marked by wavy lines. House Range from Hintze (1974, 1981a, b); Thomas Range-Drum Mountains from Lindsey (1982); Gulf 1 Gronning from McDonald (1976) and Lindsey et al (1981); Argonaut Energy 1 from Mitchell (1979) and Lindsey et al (1981); and Canyon Range from Campbell (1979).

Desert (Gilbert, 1890; Clark, 1977; Mehnert and Rowley, 1978). These units range in age from late Miocene to Holocene and are part of a trend of volcanism that continues to the south into the Black Rock volcanic field. Condie and Barsky (1972) defined seven different volcanic fields in the southern Sevier Desert and Black Rock Desert having rocks that range in age from 2.35 m.y. to 11,000-12,000 years, the majority of which are under 1 m.y. These fields have many young volcanic cones. Pavant Butte, 23 km (14 mi) south of COCORP Line 1, is 270 m (890 ft) high and is the largest of the volcanic cones. These youngest volcanic features were formed prior to, synchronous with, and after an arm of glacial lake Bonneville invaded the Sevier Desert basin (Condie and Barsky, 1972). Three cinder cones located just west of the town of Fillmore are not covered by any deposits of lake Bonneville and are thought to be as young as 5,000 years.

The Smelter Knolls volcanic field (Figure 1) consists of a single dome of rhyolite with some small outcrops of basaltic andesite and tholeiitic basalt. The basaltic andesite, rhyolite, and tholeiitic basalt yield ages of 6.1 Ma, 3.4 Ma, and 0.31 Ma, respectively (Turley and Nash, 1980). Farther north, the larger Fumarole Butte volcanic complex comprises part of the Crater Springs Known Geothermal Resource Area (Peterson and Nash, 1980) and exposes rhyolite, tholeiitic basalt, and basaltic andesite, dated at 6.1 Ma, 6.0 Ma, and 0.88 Ma, respectively.

The upper Cenozoic volcanic rocks of the Sevier Desert are offset by numerous normal faults which strike northwest to northeast. Condie and Barsky (1972) suggested that these normal faults may have been important in controlling the location of the volcanic centers. However, because the high-angle normal faults do not appear to extend through the detachment on either the COCORP data or on the previously published sections, the relationship of the high-angle faulting to the location of the volcanic centers is uncertain.

Well Data

There are five exploration wells in the central Sevier Desert, three of which have penetrated significant thicknesses of Cenozoic strata (Figure 1). A 1957 stratigraphic test of the Cenozoic formations, the Gulf 1 Gronning, was the only deep well drilled in the basin until the late 1970s. The primary objective of all the wells, except the Gulf 1 Gronning, was to test the potential of the Paleozoic rocks which underlie the basin. The stratigraphy of the Gulf 1 Gronning has been described in detail by McDonald (1976) and Lindsey et al (1981). The well was drilled in the central portion of the basin to a total depth of 2,458 m (8,064 ft). About 1,800 m (5,900 ft) of Cenozoic basin fill remains undrilled below the bottom of the well as indicated by seismic data. Although it was originally suggested that the well bottomed in rocks of Eocene or Triassic age (Heylmun, 1965; McDonald, 1976), more recent work by Lindsey et al (1981) has shown that the well penetrated only latest Oligocene and younger rocks. The strata of the well have been divided into six units (Figure 2). Five basaltic flows with an aggregate thickness of 100 m (330 ft) are interbedded with sedimentary strata in the youngest unit. The third of these flows was dated by the K-Ar whole rock method (Lindsey et al, 1981, p. 259) at 4.2 ± 0.3 Ma. The fluvio-lacustrine strata of the fifth unit have been dated by the fission track method on zircon and apatite at 25.9 ± 1.2 Ma and 27.8 ± 6.8 Ma, respectively (Lindsey et al, 1981). Ages determined from palynomorphs are in agreement with these dates.

The Argonaut Energy 1 Federal, located 11.3 km (7 mi) northeast of the Gulf 1 Gronning (Figure 1), encountered markedly different basinal sedimentary rocks. Although similar clastic strata were found down to a depth of 777 m (2,550 ft), the rest of the Tertiary section consisted of a thick lens of halite containing some anhydrite and shale layers (Figure 2). This body, seen on a seismic section published by McDonald (1976), extends from 777 m (2,550 ft) to 2,347 m (7,700 ft). Fossil pollen of Tertiary age were extracted from the salt (Mitchell, 1979). Lindsey et al (1981) suggested the existence of a closed evaporite basin in the Sevier Desert during the Oligocene. The salt in the Argonaut well may have been redeposited in this basin by erosion of the Jurassic Arapien formation, which crops out 72 km (45 mi) to the southeast.

The changing patterns of middle to late Cenozoic deposition in the Sevier Desert can be summarized as follows. During the Oligocene, voluminous amounts of rhyolitic lavas and ash-flow tuffs were erupted from source areas northwest, northeast, and south of the Sevier Desert. These rocks were eroded and redeposited in a preexisting depression. Units 5 and 6 of the Gulf 1 Gronning well, and presumably the undrilled basinal material below them, were deposited in this way. Contemporaneously, halite and anhydrite were deposited in isolated parts of the basin. During

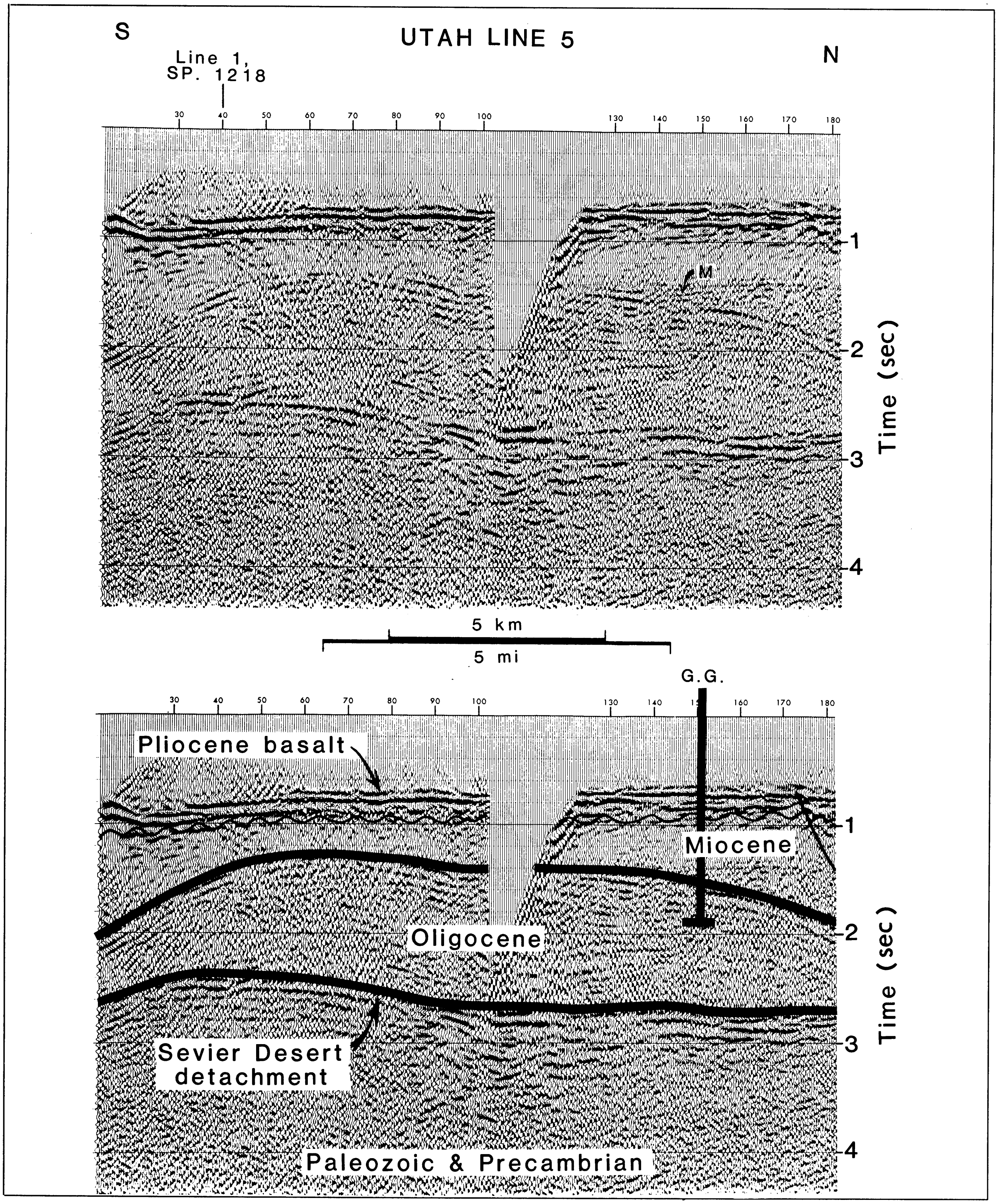


Figure 4—COCORP line 5, uninterpreted and interpreted. Sections are 1:1 for a velocity of 5,000 m/sec (16,400 ft/sec) and are not migrated. Datum is 1,432 m (4,698 ft) above sea level. G.G. = projection of Gulf 1 Gronning well, located 1,400 m (4,600 ft) east of line 5. Event M is multiple reflection.

(For Figure 3, see foldout.)

the Miocene, individual mountain blocks such as the Canyon and House Ranges and the Cricket Mountains were uplifted. Coarse sediments eroded from these rising blocks were deposited in the basin. Basaltic volcanism migrated into the area from the south during the Pliocene and the Pleistocene, producing numerous cones and flows. Glacial lake Bonneville occupied the Sevier Desert basin during the Pleistocene, leaving shoreline deposits and geomorphic constructions, which are exposed on the flanks of the surrounding ranges and on some of the volcanic cones.

COCORP DATA

COCORP recorded three seismic lines in the central portion of the Sevier Desert (Figure 1). Line 1 (Figure 3, foldout) crossed the basin from west to east, perpendicular to strike. Line 5 (Figure 4), a north-south-trending cross line, is parallel to strike across the deepest part of the basin and provides important three-dimensional control. Line 6 runs north-south along the eastern pediment of the House Range. Line 6 did not cross basinal sedimentary strata of significant thickness and will not be discussed further here. The acquisition, processing, and general interpretation of the entire west-central Utah survey were described by Allmendinger et al (1983).

The Sevier Desert is almost 90 km (56 mi) wide at the latitude of the COCORP survey. However, most of the desert is not underlain by one continuous structural basin, but consists, rather, of one major half graben, one minor half graben, and broad areas extending from the adjacent ranges that are covered by less than 1 km (3,300 ft) of sediments. The asymmetric form of the Sevier Desert is clearly resolved by COCORP line 1, a portion of which is shown in Figure 3. The largest structural basin is restricted to the central and eastern 30 km (19 mi) of the desert, beneath vibration points (VP) 1,150-1,450. This Tertiary basin has a maximum depth of at least 4,500 m (14,800 ft). A smaller graben, with a depth of 2,000 m (6,600 ft) lies farther west, beneath VP 950-1,050. Paleozoic and Precambrian rocks of the Cricket Mountains extend northward beneath a thin cover of sedimentary strata and form the allochthonous block beneath VP 1,050-1,220.

The interpretation of the COCORP seismic reflection data was aided by the availability of other geophysical and geologic data in the Sevier Desert. Gravity data reveal the trend of the largest structural graben of the Sevier Desert basin as a north-south trough of low Bouguer gravity values (Cook et al, 1975). McDonald (1976) published five seismic lines in the vicinity of the COCORP survey (Figure 1), and various logs from wells in the desert were examined.

Sevier Desert Detachment

One of the most striking features on COCORP line 1 is the west-dipping multicyclic event that extends from near the surface at VP 1,480 to 4.5-sec two-way traveltime beneath VP 950 (Figure 3) and to 5.2-sec two-way traveltime beneath VP 800. This horizon, originally seen on shallow seismic lines published by McDonald (1976), is a low-angle Cenozoic normal fault, termed the Sevier Desert detachment by Allmendinger et al (1983). Although it has been suggested that the Sevier Desert detachment is a Mesozoic thrust fault that has been reactivated with normal displacement (McDonald, 1976), palinspastic restorations by Sharp (1984) indicate that it is just as likely a new Cenozoic normal fault over much of its extent. The multicyclic character of this event may represent sedimentary layering above and/or below the detachment, or a zone of cataclasis. The Sevier Desert detachment has been traced over 70 km (43 mi) perpendicular to strike and to depths of 12-15 km (7.5-9.3 mi) (Allmendinger et al, 1983). The detachment ranges in dip from 8° to 15°W, with an average of 11°W (Figure 5). The Sevier Desert detachment does not appear to be offset by the high-angle normal faults which disrupt the strata above it; however, minor displacements of the detachment surface are possible. These high-angle normal faults cut a 4.2 ± 0.3 Ma basalt flow (Lindsey et al, 1981, p. 259), hence documenting normal displacement along the detachment at least as recently as the middle Pliocene. Elsewhere within the Sevier Desert, other high-angle faults show evidence of recent activity as indicated by fault scarps and offsets in Pleistocene sediments of lake Bonneville (Bucknam and Anderson, 1979; Zoback, 1983; Crone and Harding, 1984). Restoration of hanging wall and footwall truncations of Mesozoic features yields 28-38 km (17-24 mi) of middle and late Cenozoic extension along the Sevier Desert detachment (Sharp, 1984).

Depth contours on the detachment (Figure 5) were derived from well data, from the conversion of traveltime to depth from the COCORP data, and from seismic lines published by McDonald (1976). Velocity functions for this conversion were obtained from sonic logs from the Argonaut Energy 1 Federal well, the Cominco American 2 Beaver River well, the ARCO 1 Pavant Butte well, and from interval velocities derived from the COCORP data. The detachment generally has a north-south strike throughout the region of Figure 5, except in the northern area. The detachment does have a broad rise of about 300 msec in the southern half of line 5 (Figure 4), but otherwise is approximately horizontal over the extent of the line. The structural dome on the detachment in the northeast corner of Figure 5 was discussed by Mitchell (1979). It is overlain by a salt lens with a maximum thickness of 1,571 m (5,154 ft). Velocity "pull-up" effects (due to the salt) have been removed by the depth conversion process. The timing and method of formation of the dome are unknown. However, a possibly important spatial relationship is that a major Mesozoic tear fault in the Leamington area has been projected westward beneath the Sevier Desert (Morris, 1983). The dome on the detachment is located slightly north of the inferred position of this tear fault.

Figure 3—COCORP line 1, uninterpreted and interpreted. These sections migrated and are 1:1 for a velocity of 5,000 m/sec (16,400 ft/sec). Datum is 1,432 m (4,698 ft) above sea level. G.G. = projection of Gulf 1 Gronning well, located 11 km (6.8 mi) north of line. Dotted line is interpreted position of Miocene-Oligocene boundary. Wavy lines indicate erosional unconformities.

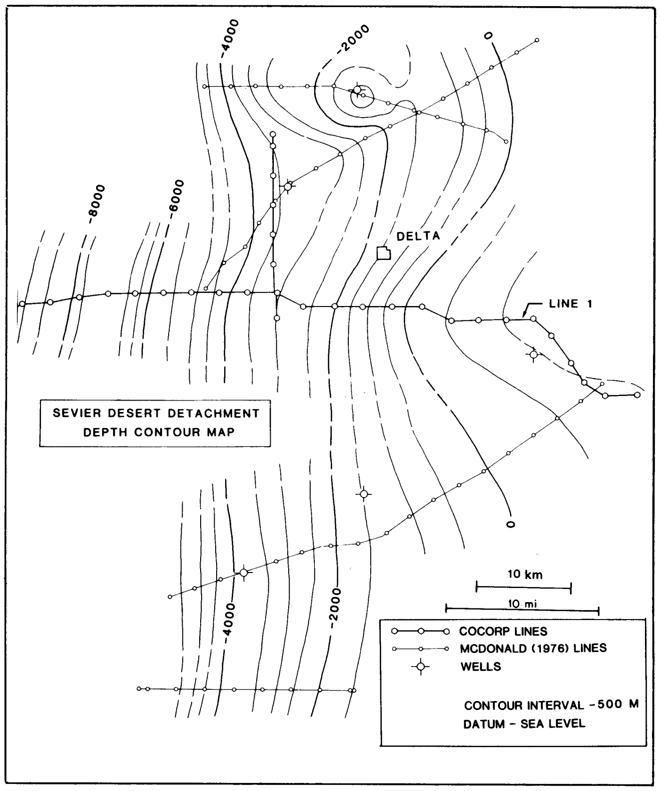


Figure 5—Depth contour map of Sevier Desert detachment.

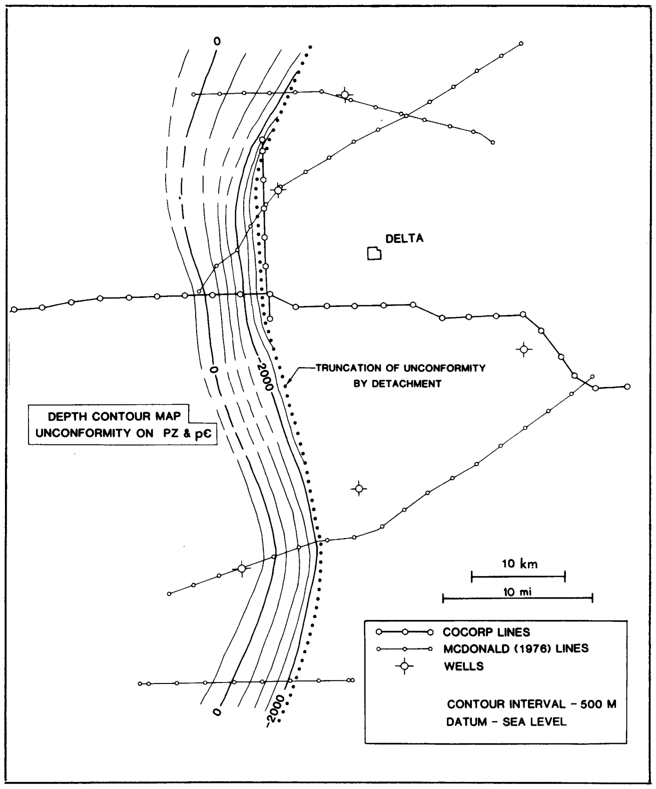


Figure 6—Depth contour map of unconformity separating Paleozoic and Precambrian rocks from strata of central graben of Sevier Desert basin.

Although the extent of the Sevier Desert detachment to the north and south of the study area is unknown, it underlies at least 4,000 km^2 (1,500 mi^2) of the desert. Farther west, COCORP line 1 shows that the detachment extends beneath the eastern House Range where the detachment coincides with several splays of probable Mesozoic origin.

Paleozoic-Tertiary Unconformity

In the upper plate of the Sevier Desert detachment, an erosional unconformity separates the lower strata of the Tertiary basin from older rocks. This unconformity appears as an east-dipping event beginning at 0.8 sec beneath VP 1,150 and ending at 2.6 sec beneath VP 1,225 (Figure 3). The unconformity surface has an average dip of 15°-25°E in this area (Figure 6). The Cominco American 2 Beaver River (total depth 4,021 m or 13,192 ft), drilled 30 km (19 mi) south of line 1 and adjacent to one of the seismic lines published by McDonald (1976), encountered Precambrian metasedimentary and Paleozoic carbonate rocks beneath the unconformity. A dipmeter survey for that well shows that the unconformity is somewhat angular (Table 1). The graben on the west side of the normal fault at VP 1,050 contains several smaller normal faults that cut both the Paleozoic strata and the overlying Cenozoic rocks (Figure 3). The unconformity is seen in surface exposure on the east side of the House Range, and to the north in the Little Drum Mountains.

The Gulf 1 Gronning well (total depth 2,458 m or 8,064 ft) bottomed in interbedded red sandstone, siltstone, and claystone of middle Oligocene age (Lindsey et al, 1981). The age and lithologic type of the remaining undrilled basinal rocks are unknown. However, there is no discernable change in the seismic character of the basin at these depths (Figure 3). Hence, the lowest portion of the basin may consist of sedimentary material similar to that encountered in the base of the Gulf well with perhaps some nonreflective volcanic units as well. The 26-28 Ma sequence (Lindsey et al, 1981) at 2,109 m (6,919 ft) (1.6 sec) has a migrated apparent dip of 18°-25°E along the trend of the COCORP line (Figure 3). The reflection package also has a component of southward dip as seen on line 5 (Figure 4), although the southward dip is exaggerated on the seismic section due to the offset in line 5 at VP 40. The Oligocene strata overlie Paleozoic and Precambrian strata of the Cricket Mountain block (Hintze, 1973), which has probably moved westward down the detachment. These basal strata overlying the Precambrian can be traced both northward and southward on the seismic sections (Figure 6). East of the basin axis, these strata are broken up into smaller structural blocks with different orientations.

Miocene conglomeratic deposits at depths of 1,072 m (3,517 ft) to 1,308 m (4,291 ft) in the Gulf well may be correlated with a reflection sequence on COCORP line 1 that dips 15°-20°E (migrated) (Figure 3). The Miocene conglomerates were deposited on top of the older strata which overlie the Cricket Mountain block, and elsewhere they appear to have accumulated in structural depressions formed by the moving blocks (VP 1,235-1,285; also examples in McDonald, 1976).

Table 1. Unit Dips and Angular Unconformities in Sevier Desert Basin

	West Side of Basin		
	COCORP Line 1	Cominco American 2 Beaver River*	Center of Basin
Pliocene basalt	1°-3°E		7°E
Basalt/Oligocene	17°-22°**		
Basalt/Miocene			12°**
Miocene			19°E
Oligocene	18°-25°E	30°-40°E	
Oligocene(?)/Paleozoic and Precambrian		10°-30°**	
Paleozoic and Precambrian		10°-20°SE	

*From dipmeter survey.

**Angle between beds above and below unconformity, not with respect to horizontal.

Late Tertiary Unconformity

The tilted middle Oligocene and Miocene strata on the west side of the basin are truncated beneath the Pliocene basalt, forming an angular unconformity. This surface is clearly seen on line 1, extending from 0.7 sec under VP 1,140 to about 1.2 sec under VP 1,240 (Figure 3). The unconformity also extends farther west to VP 1,050, but in this area it probably truncates Paleozoic rocks, not the middle Tertiary strata. The basalts above the unconformity generally dip 1°-3°E west of the central axis of the basin, but eastward are more complexly deformed.

The complex, three-dimensional nature of the angular unconformity beneath the basalt sequence can be seen on COCORP line 5 (Figure 4). The basalts show almost no change in depth north of the offset in the line at VP 40. This geometry contrasts strongly with the arched shape of Oligocene and Miocene units deeper in the section.

The relations of the Pliocene basalt to the underlying Tertiary strata east of VP 1,240 are less clear. In the central structural low of the Sevier Desert basin between VP 1,240 and 1,290, the band of high-amplitude reflections corresponding to the basalt thickens (from 300 to 500-msec two-way time) and increases in dip (Figure 3). Although some angular discordance is apparent between the basalt and the Miocene(?) strata, that discordance is smaller than farther west, and the entire package of Cenozoic strata has a smoother, fanning-upward aspect. Thus, although the angular unconformity indicates a period of quiescence and erosion (and by inference, episodic extension), subsidence in the central part of the basin appears to have been more continuous, suggesting only relatively minor hiatuses in extension between the Miocene and Pliocene epochs.

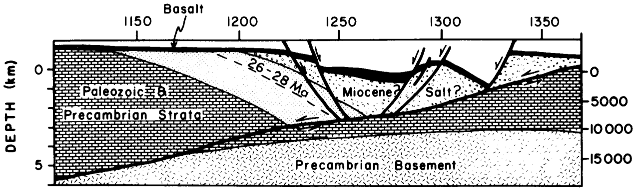


Figure 7—Depth section of central graben of Sevier Desert basin. No horizontal exaggeration.

Beneath VP 1,285-1,320, reflections probably corresponding to the basalt are folded or draped into a dome bounded on both flanks by west-dipping normal faults (Figure 3). A dome with a similar appearance is seen on a seismic line 21 km (13 mi) to the north (McDonald, 1976, his Plate II) and contains the thick salt lens drilled by the Argonaut Energy 1 well. The northern dome has at least two major differences from the one on COCORP line 1: (1) the basalt flows are truncated against the side of the dome, and (2) the detachment has a major structural high directly beneath the dome. The basalt sequence appears to cover the top of the dome on COCORP line 1, and no corresponding structural high is beneath it. However, about a 200-msec rise on the Sevier Desert detachment is beneath the western half of the dome on COCORP line 1. This rise is probably an artificial pull-up effect from high-velocity material within the dome. The dome may contain some evaporites, but on the basis of the lack of a more substantial velocity pull-up beneath the entire dome, it is probably not composed primarily of halite, unlike its northern counterpart. The basalt flows covering the dome may be tentatively correlated farther east with the event beneath VP 1,320-1,390 at 0.7 sec.

The basalts are disrupted by several small normal faults in the area between VP 950 and 1,100, and by large normal faults at VP 1,050, 1,230-1,240, and 1,290 (Figure 3). Throughout the basin, the basalt sequence has a complex geometry due to the extensional deformation. This complex geometry does not permit the construction of a depth contour map of the level of the Pliocene basalts with only the few seismic lines available.

DISCUSSION: TIMING AND MAGNITUDE OF CENOZOIC DISPLACEMENT

The central Sevier Desert basin formed as a result of movement on the underlying Sevier Desert detachment, and thus the geometric relations of sedimentary and volcanic packages in the basin must record, in a complex fashion, the history of Cenozoic extension in the region. In this discussion, the following assumptions are made: (1) units that do not significantly change thickness laterally were not deposited during periods of active extension; (2) a fanning-upward, wedge-shaped geometry is typical of growth faulting and represents syntectonic deposition; and (3) angular unconformities within the basin represent periods

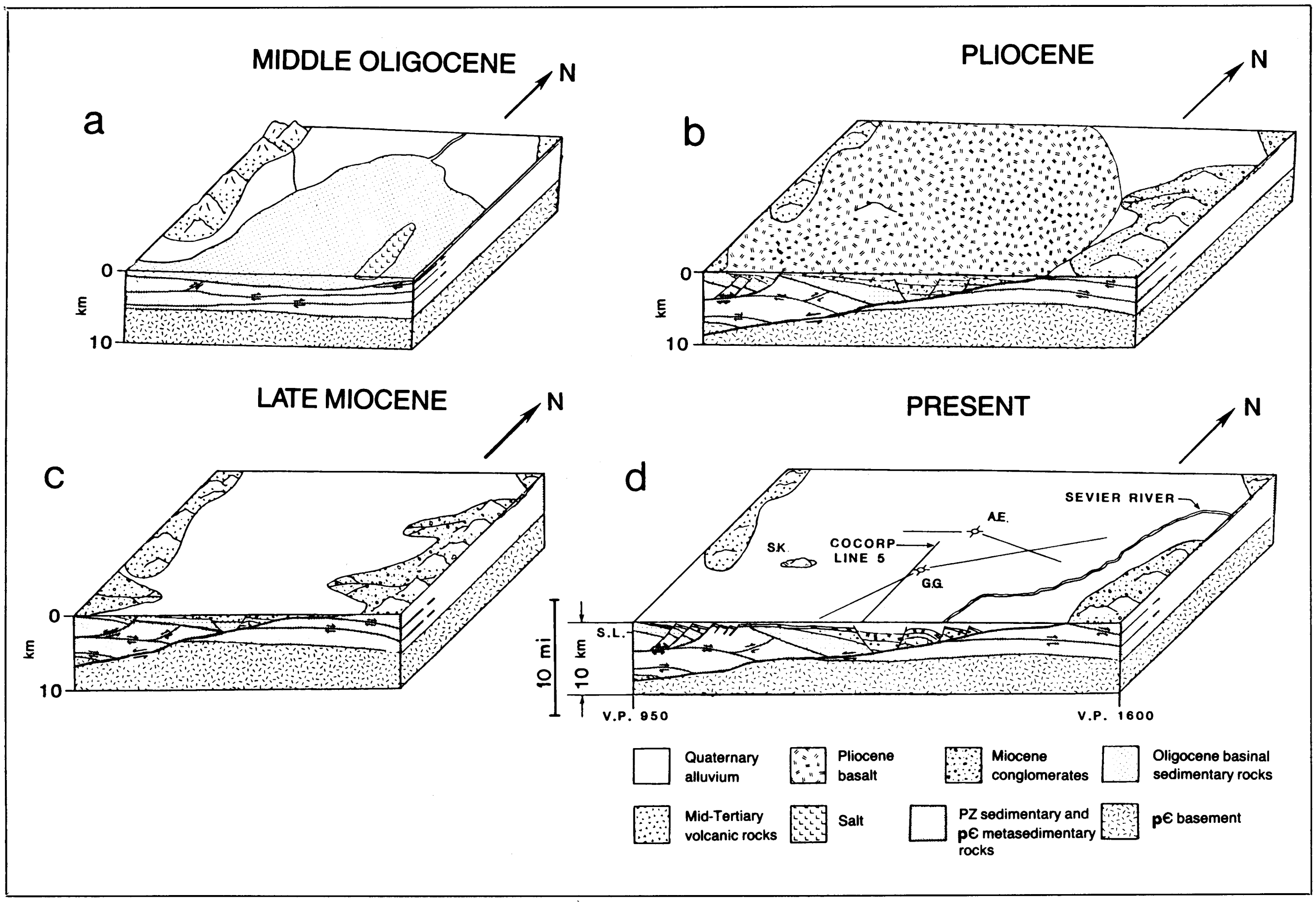


Figure 8—Reconstruction of Sevier Desert. (a) Middle Oligocene prior to extension. Front of block is along the trend of COCORP line 1. Location of Mesozoic thrust faults in Paleozoic strata and Precambrian metasedimentary rocks based on Sharp (1984). (b) Late Miocene after uplift of Canyon and House Ranges. (c) Middle Pliocene during outpouring of basaltic flows. (d) Modern Sevier Desert basin. S.K. = Smelter Knolls; A.E. = Argonaut Energy 1 well; G.G. = Gulf 1 Gronning well. Narrow lines are locations of two northerly lines published by McDonald (1976).

of erosion, inactive subsidence, and, by inference, episodic tectonic activity of unknown duration. Various features affecting the validity of these assumptions (e.g., shifting depocenters and source areas, etc) cannot be adequately evaluated due to lack of good age control on most of the Tertiary rocks in the region, but nonetheless suggest some caution. The geometry of units in the Sevier Desert basin is shown in Figure 7.

The oldest deposits in the basin, probably Oligocene in age, rest with gentle angular unconformity on Paleozoic and Precambrian strata. The reflection sequence from rocks 26-28 Ma and older dips about 18°-25°E (Table 1) and shows little change in thickness laterally on COCORP line 1, although on north-trending line 5 it has a complex geometry which may be indicative of either original depositional processes or perhaps poorly imaged oblique-trending normal faulting at a high angle to line 5. Because these older deposits do not change thickness in the direction of movement of the detachment, it is likely that they mostly predate the detachment (Figure 8a). The angularity of the unconformity beneath the deposits is probably due to deformation associated with Cretaceous and early Tertiary thrusting.

The Oligocene-Miocene boundary is not well resolved by well data, and the seismic data show few reflections from the interval between the upper Oligocene strata and the Pliocene basalt. The depth section (Figure 7) suggests that Miocene units must thicken and fan eastward. These relations indicate that movement on the detachment must have begun by the Miocene and perhaps by the latest Oligocene. Relations in the Drum Mountains and Thomas Range indicate that the major phase of extension occurred between 21 and 7 Ma (Lindsey, 1982), but it is not known whether movement on the Sevier Desert detachment controlled that deformation.

A hiatus in basin development is marked by the angular unconformity beneath the Pliocene basalts, which dip only 1°-3°E on the west side of the basin. The temporal extent and significance of this event are uncertain because the unconformity is much less pronounced in the center of the basin where the basalts thicken and dip about 7°E. Reflections from Miocene(?) units beneath the basalt in the basin center dip about 10° more steeply (Table 1). This relation may indicate that the basin became segmented into smaller structural blocks during the Miocene, with deposition becoming concentrated in continuously subsiding struc-

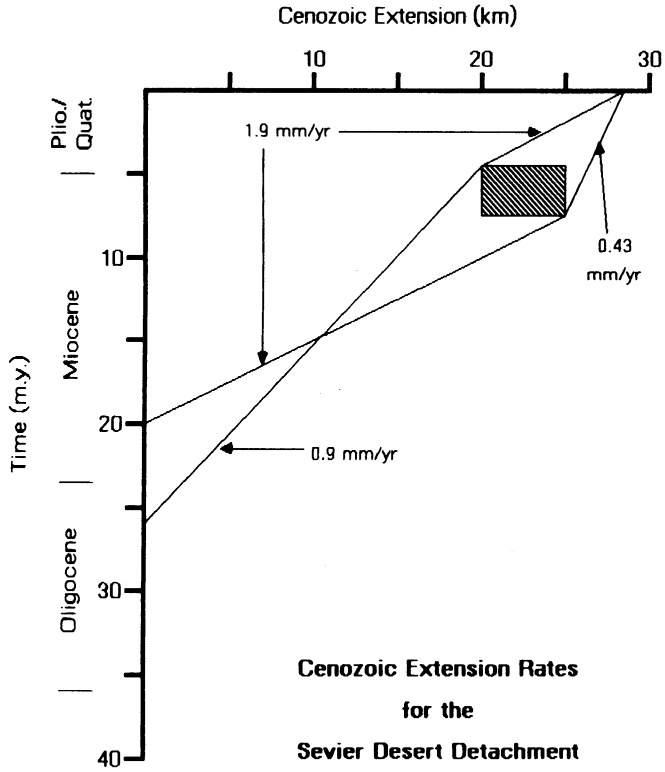


Figure 9—Range of reasonable extension rates through time for central Sevier Desert basin. Timing from this study; magnitudes of extension from Sharp (1984). Ruled box represents uncertainty in age of unconformity and amount of extension.

tural lows between those blocks. This segmentation may represent the breakup of the upper plate of the Sevier Desert detachment at some point after the initiation of the fault surface (Figure 8b).

The thickening of the Pliocene basalts within the central part of the Sevier Desert basin indicates that some subsidence and extension were in progress during their eruption and deposition (Figure 8c). Normal faulting continued after the basalts were deposited and may have characterized the region until recently (Figure 8d) (Bucknam and Anderson, 1979; Zoback, 1983).

Though imprecise, these timing data may be combined with estimates of the magnitude of extension in this part of Utah to determine the rates of extension during Cenozoic time. Palinspastic restorations by Sharp (1984) suggest that the total displacement on the Sevier Desert detachment is between 28 and 38 km (17 and 24 mi), with the lower figure regarded as the more likely. Estimates of extension following the deposition of the basalt are uncertain because its extent on the east side of the basin is not well resolved. A reasonable range for post-basalt extension, however, is 2 to 8 km (1.2 to 5.0 mi).

A plot of these extension estimates against time (Figure 9) shows that the rate of Cenozoic extension in the Sevier Desert region has probably ranged between 0.4 and 1.9 mm/year (0.016-0.075 in./year). Of greater interest, however, is that within the admittedly large uncertainty of the data, no resolvable difference exists in the rates of extension between the periods prior to and following the eruption of the latest Miocene-Pliocene basalts (about 7 to 3 Ma, based on surface and drill-hole dates). The applicability of these numbers to other parts of the Basin and Range Province is unknown. Seismic reflection data from other parts of the province show great variability in basin geometry, and the regional distribution of low-angle detachments is poorly understood (Effimoff and Pinezich, 1981; Anderson et al, 1983). With respect to the major question of whether there were one or two episodes and styles of extension in the Basin and Range, the Sevier Desert data indicate that only one type of extension has occurred (that controlled by low-angle faults), with two stages in timing separated by a period of inactivity of unknown, but probably short, duration.

CONCLUSIONS

Seismic data collected by COCORP in west-central Utah provide important information on the geometry of extension beneath the Sevier Desert. The timing of this extension may reflect the history of Cenozoic tectonism in the east-central portion of the Basin and Range Province. The nature and history of this extension can be summarized as follows.

1. Extension in the upper and middle crust beneath the Sevier Desert occurred primarily by movement along the Sevier Desert detachment, a low-angle normal fault of regional extent.
2. The orientations of the sedimentary and volcanic strata of the Sevier Desert basin reflect the history of displacement along the Sevier Desert detachment. The initial movement along the detachment began after the deposition of the middle Oligocene fluvio-lacustrine strata in a previously existing depression.
3. Miocene conglomeratic rocks were deposited across these blocks and accumulated to greater thicknesses in structural depressions caused by the separation of the blocks. Movement during this first stage continued throughout most of the Miocene.
4. A hiatus in movement along the detachment occurred prior to the middle Pliocene, and the tilted older strata in the allochthon were truncated by erosion.
5. A later stage of movement began after several basalt flows spread over the basin in the middle Pliocene. This stage continues to the present.
6. Cenozoic strata of the basin are younger to the east because of the unidirectional movement of the blocks of the extensional allochthon. This westward movement created the structural depression of the central Sevier Desert basin.

REFERENCES CITED

Allmendinger, R. W., J. W. Sharp, D. Von Tish, L. Serpa, L. Brown, S. Kaufman, J. E. Oliver, and R. B. Smith, 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range Province, Utah, from COCORP seismic reflection data: Geology, v. 11, p. 532-536.

Anderson, R. E., M.-L. Zoback, and G. A. Thompson, 1983, Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range Province, Nevada and Utah: GSA Bulletin, v. 94, p. 1055-1072.

Armstrong, R. L., 1968, Sevier orogenic belt in Nevada and Utah: GSA Bulletin, v. 79, p. 429-458.

——— 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range Province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochimica et Cosmochimica Acta, v. 34, p. 203-232.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: GSA Bulletin, v. 81, p. 3513-3535.

Bucknam, R. C., and R. E. Anderson, 1979, Map of fault scarps on unconsolidated sediments, Delta 1° by 2° quadrangle, Utah: USGS Open-File Report 79-366, scale 1:250,000.

Campbell, J. A., 1979, Middle to late Cenozoic stratigraphy and structural development of the Canyon Range, central Utah: Utah Geology, v. 6, p. 1-15.

Clark, E. E., 1977, Late Cenozoic volcanic and tectonic activity along the eastern margin of the Great Basin, in the proximity of Cove Fort, Utah: Brigham Young University Geology Studies, v. 24, p. 87-114.

Condie, K. C., and C. K. Barsky, 1972, Origin of Quaternary basalts from the Black Rock Desert region, Utah: GSA Bulletin, v. 83, p. 333-352.

Coney, P. J., 1978, Mesozoic-Cenozoic Cordilleran plate tectonics, *in* Cenozoic tectonics and regional geophysics of the western Cordillera: GSA Memoir 152, p. 33-50.

Cook, K. L., J. R. Montgomery, J. T. Smith, and E. F. Gray, 1975, Simple Bouguer gravity anomaly map of Utah: Utah Geological and Mineral Survey Map 37.

Crone, A. J., and S. T. Harding, 1984, Relationship of late Quaternary fault scarps to subjacent faults, eastern Great Basin, Utah: Geology, v. 12, p. 292-295.

Effimoff, I., and A. R. Pinezich, 1981, Tertiary structural development of selected valleys based on seismic data: Basin and Range Province, northeastern Nevada: Philosophical Transactions of the Royal Society of London, Series A, v. 300, p. 435-442.

Gilbert, G. K., 1890, Lake Bonneville: USGS Monograph 1, 438 p.

Heylmun, E. B., 1965, Reconnaissance of the Tertiary sedimentary rocks in western Utah: Utah Geological and Mineralogical Survey Bulletin 75, 38 p.

Hintze, L. F., 1973, Geologic history of Utah: Brigham Young University Geology Studies, v. 20, part 3, 181 p.

——— 1974, Preliminary geologic map of the Notch Peak quadrangle, Millard County, Utah: USGS Miscellaneous Field Studies Map 636, scale 1:48,000.

——— 1980, Geologic map of Utah: Utah Geological and Mineral Survey, scale 1: 500,000.

——— 1981a, Preliminary geologic map of the Marjum Pass and Swasey Peak SW quadrangles, Millard County, Utah: USGS Miscellaneous Field Studies Map 1332, scale 1:24,000.

——— 1981b, Preliminary geologic map of the Swasey Peak and Swasey Peak NW quadrangles, Millard County, Utah: USGS Miscellaneous Field Studies Map 1333, scale 1:24,000.

Lindsey, D. A., 1982, Tertiary volcanic rocks and uranium in the Thomas Range and northern Drum Mountains, Juab County, Utah: USGS Professional Paper 1221, 71 p.

——— R. K. Glanzman, C. W. Naeser, and D. J. Nichols, 1981, Upper Oligocene evaporites in basin fill of Sevier Desert region, western Utah: AAPG Bulletin, v. 65, p. 251-260.

McDonald, R. E., 1976, Tertiary tectonics and sedimentary rocks along the transition: Basin and Range Province to Plateau and Thrust Belt Province, Utah: Rocky Mountain Association of Geologists Symposium, p. 281-317.

Mehnert, H. H., P. D. Rowley, and P. W. Lipman, 1978, K-Ar ages and geothermal implications of young rhyolites in west-central Utah: Isochron/West, no. 21, p. 3-7.

Mitchell, G. C., 1979, Stratigraphy and regional implications of the Argonaut Energy No. 1 Federal, Millard County, Utah, *in* G. C. Newman, ed., Basin and Range symposium and Great Basin field conference: Rocky Mountain Association of Geologists, p. 503-514.

Morris, H. T., 1983, Interrelations of thrust and transcurrent faults in the central Sevier orogenic belt near Leamington, Utah, *in* Tectonic and stratigraphic studies in the eastern Great Basin: GSA Memoir 157, p. 75-81.

Peddy, C., L. Brown, and S. Klemperer, 1985, in press, Interpreting the deep structure of rifts with synthetic seismic sections: American Geophysical Union, Geodynamics Series.

Peterson, J. B., and W. P. Nash, II, 1980, Geology and petrology of the Fumarole Butte volcanic complex, Utah, *in* M. Smith, ed., Studies in late Cenozoic volcanism in west-central Utah: Utah Geological and Mineral Survey Special Study 52, p. 34-58.

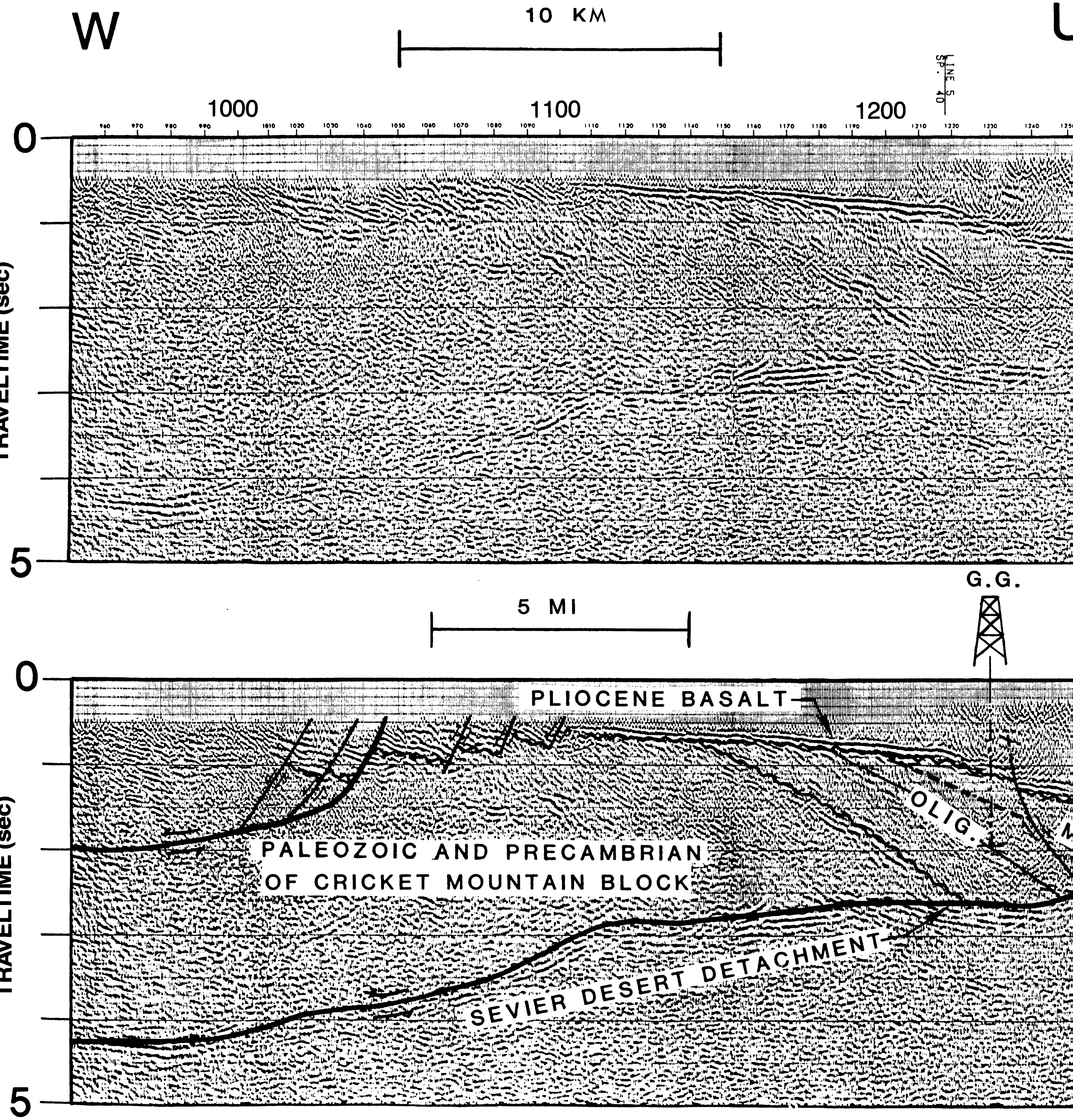
Sharp, J. W., 1984, West-central Utah: palinspastically restored sections constrained by COCORP seismic reflection data: Master's thesis, Cornell University, Ithaca, New York, 60 p.

Turley, C. H., and W. P. Nash, II, 1980, Petrology of late Tertiary and Quaternary volcanism in western Juab and Millard Counties, Utah, *in* M. Smith, ed., Studies in late Cenozoic volcanism in west-central Utah: Utah Geological and Mineral Survey Special Study 52, p. 1-33.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range Province: nappe tectonics in an extending orogen: Nature, v. 291, p. 645-648.

Zoback, M. L., 1983, Structure and Cenozoic tectonism along the Wasatch fault zone, Utah, *in* Tectonic and stratigraphic studies in the eastern Great Basin: GSA Memoir 157, p. 3-27.

——— R. E. Anderson, and G. A. Thompson, 1981, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range Province of the western United States: Philosophical Transactions of the Royal Society of London, Series A, v. 300, p. 407-434.


W
10 KM
LINE 5
SP. 40
1000
1100
1200
0
5
TRAVELTIME (sec)
5 MI
G.G.
0
PLIOCENE BASALT
OLIG.
PALEOZOIC AND PRECAMBRIAN
OF CRICKET MOUNTAIN BLOCK
SEVIER DESERT DETACHMENT
5
TRAVELTIME (sec)

UTAH LINE 1