Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic-reflection data

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ABSTRACT

COCORP seismic-reflection data collected from the eastern Basin and Range in west-central Utah provide information on Cenozoic extensional tectonics, Mesozoic thrusting, and their interrelationships. Those data show a series of remarkably continuous, low-angle reflectors that extend more than 120 km perpendicular to strike and can be traced as deep as 15–20 km. Over that distance, none of these events are significantly cut by any high-angle normal faults. A major detachment beneath the Sevier Desert can be traced from a surface zone of normal faulting to a depth of 12–15 km, with a regional apparent westward dip of 12°. Tentative correlation of upper- and lower-plate events suggests 30–60 km of extensional displacement on this detachment. Whether this structure is a reactivated Mesozoic thrust is uncertain. West-steepening splays off the end of the detachment reach depths of 20 km and may represent a major Mesozoic ramp or zones of distributed ductile shearing during extension. Some events are interpreted to be Mesozoic thrusts, of which at least one (beneath the House Range) has been reactivated during the Cenozoic. The Snake Range decollement dips gently east and has a sense of Cenozoic displacement opposite to that of other Cenozoic detachments farther east. Deep events are most numerous beneath the east side of the Sevier Desert where they occur to depths of 30 km, at the top of or perhaps partly within the anomalously low velocity upper mantle.

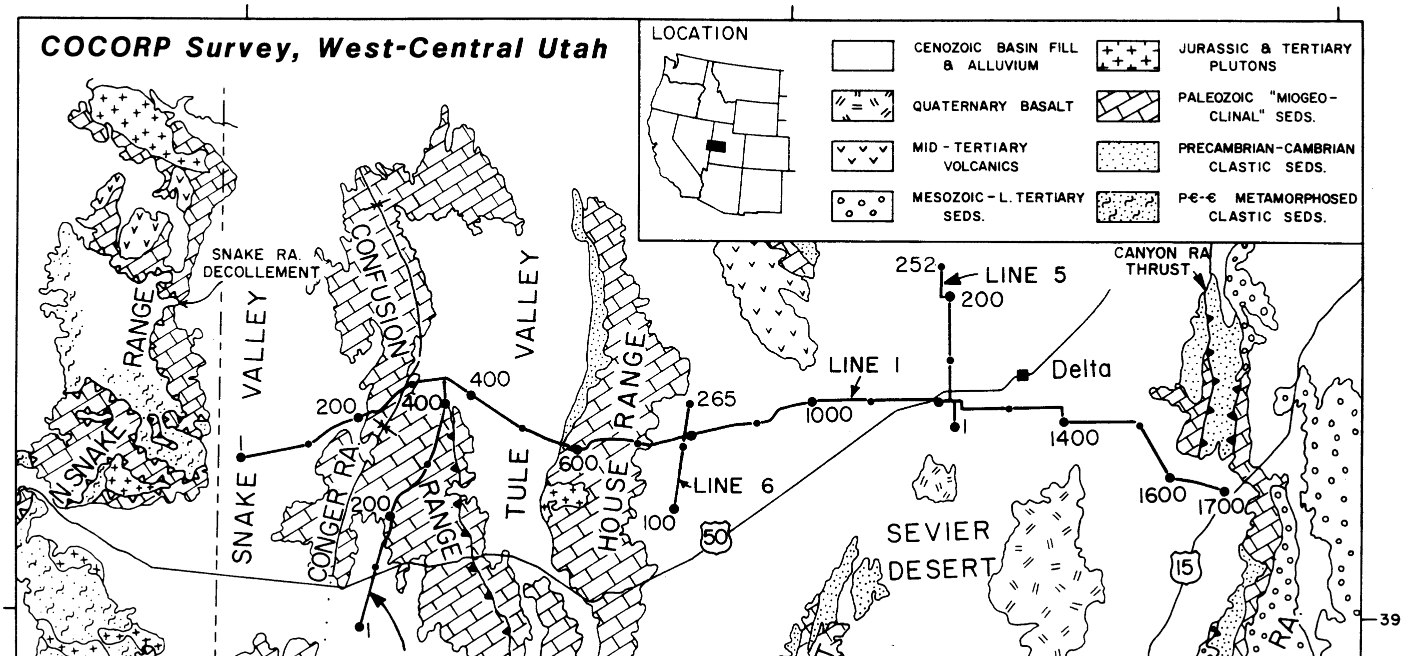

Figure 1. Location map and generalized geologic setting of COCORP lines in west-central Utah.

INTRODUCTION

The Basin and Range province, the largest intracontinental rift in the world, contains important clues to the deep structure of continental rifts, the nature of "transitional crust," and the relations of rifting to prior thrust faulting. Models of Basin and Range extension include the classic horst and graben geometry with steeply dipping normal faults; listric normal fault-tilted block geometry with faults soling into a regional, subhorizontal zone of decoupling; and crustal penetrating master detachments (Stewart, 1980; Zoback et al., 1981; Eaton, 1980; Smith, 1978, 1982; Wernicke, 1981). The western extent of Mesozoic thrusts in the region is also a key problem (Armstrong, 1982).

Data collected by the Consortium for Continental Reflection Profiling (COCORP) in west-central Utah suggest that crustal structure is dominated by low-angle detachment surfaces (interpreted on the basis of laterally coherent seismic packages separated by multicycle reflections) that can be traced over horizontal distances of 70 km or more and to depths between 12 and 15 km. Many of these low-angle reflectors have, on a regional scale, a seismic character commonly associated with thrusts. However, across at least 120 km, no high-angle normal faults significantly displace these reflectors, suggesting that the detachments are in their most recent history low-angle normal faults. Thrust faults can be inferred from the seismic data on the basis of correlation with similar reflection packages, in combination with known stratigraphic and structural relations at the surface.

TECTONIC SETTING

The region of the COCORP survey is known to have been deformed by both Cretaceous–early Cenozoic thrusting and middle and late Cenozoic extension (Hintze, 1973). Key Mesozoic features include (Fig. 1) the Canyon and Pavant Range thrusts (Armstrong, 1968; Burchfiel and Hickcox, 1972), the Jurassic intrusion in the House Range (Hintze, 1974), and the Confusion Range synclinorium (Hose, 1977). In addition, Mesozoic thrusts are known in the subsurface east of the COCORP line, and some probably project westward at depth beneath the seismic survey.

Cenozoic structures include high-angle normal faults, typically regarded as having produced the characteristic basin and range morphology of the region during the past 15 m.y., and somewhat older low-angle normal faults that predate the present topography and appear to have initially formed contemporaneously with the mid-Cenozoic (≃30 m.y. B.P.) "ignimbrite flareup" of the Great Basin (Zoback et al., 1981). Prior to the COCORP survey, two low-angle detachments were known from surface and shallow subsurface data. The Snake Range decollement, originally considered to be the basal decollement for Mesozoic thrusts (Misch, 1960), has more recently been suggested to have substantial extensional movements as recently as 17 m.y. ago (Lee et al., 1970; Armstrong, 1972; Miller et al., 1982). In the Sevier Desert region, 4 s industry seismic-reflection data published by McDonald (1976) first showed that Cenozoic normal faults do not cut a prominent low-angle, west-dipping reflection that was interpreted as a detachment surface.

Geophysical data in the survey area indicate that the crust is 25–30 km thick, that the upper mantle has an anomalously low velocity (P_n = 7.4 km/s), and that a regional Bouguer gravity high is characteristic (Cook, 1969; Eaton et al., 1978; Mabey et al., 1978; Smith, 1978). Refraction and earthquake data have been used to infer a crustal low-velocity zone and brittle-ductile transition at 8–15 km depth (Smith, 1978, 1982; Eaton, 1980). Fault-plane solutions of crustal earthquakes generally do not indicate seismic slip on low-angle fault surfaces (Smith, 1982). Industry-donated reflection data from western Utah have also been interpreted by Smith (1982) to show several low-angle faults at mid- to upper-crustal depths; he has related this to a thermal-mechanical model to account for the limiting depths to a hypothesized regional brittle-ductile transition.

DATA ACQUISITION AND PROCESSING

Four seismic-reflection lines were shot—a 170 km east-west main line and three cross lines of 40, 16, and 25 km lengths (Fig. 1). Because of space limitations, the cross lines are discussed here only briefly. A 96-channel recording system was used with a 100-m station spacing, producing near and far offsets of 0.4 km and 9.9 km, respectively. Vibrating and recording times were adjusted to produce 20 s of common depth point (CDP) stacked data, corresponding to about 60 km depth. Vibrating every station (5 vibrators × 8 sweeps/station) resulted in nominal 48-fold data.

Processing of the data has followed a standard sequence that includes correlation before stack, elevation statics corrections, CDP gathering, minor filtering, mute and velocity analyses, normal moveout (NMO) corrections, and stacking. Because there is little cultural noise over most of the line, very little trace editing was required. Mutes were picked both before and after application of NMO. Velocity analysis, using velocity spectra and constant velocity stacks at 200 m/s increments, were carried out every 10 to 50 CDPs (about every 5–25 stations), depending on lateral complexities. Because the sections displayed here (Fig. 2) are not migrated, dipping reflections on the time sections will have shallower dips and will be slightly displaced laterally relative to the corresponding features in the crust. Deconvolution suggests that multiple cyclicity is not a major problem. Because variable near-surface velocities are common in the Basin and Range, a depth section (Fig. 3) based on interval velocities (calculated from stacking velocities and refraction experiments) was constructed to remove velocity pull-up effects inherent in a time section.

COCORP RESULTS FROM WEST-CENTRAL UTAH

Sevier Desert Detachment

The detachment first observed by McDonald (1976), here referred to as the Sevier Desert detachment, can be seen to extend much farther west and deeper on COCORP line 1 (event A, Fig. 2). It can be traced from the surface at the west side of the Canyon Range [about vibration point (VP) 1525] to about 5 s (12–15 km) beneath VP 800 east of the House Range as a relatively simple, remarkably continuous three- or four-cycle band of reflections. Its average dip over that 72 km lateral distance is less than 12° W, but in detail the geometry of the detachment surface is more complex. The depth section (Fig. 3) shows the detachment sharply increasing in dip from 8° to 16° at VP 1200 and becoming more gently dipping again west of VP 950. Cross lines 5 and 6 indicate that line 1 is perpendicular to strike and that the major features are not a result of "sideswipe."

The COCORP data corroborate on a more regional scale McDonald's conclusion that normal faults cutting middle and

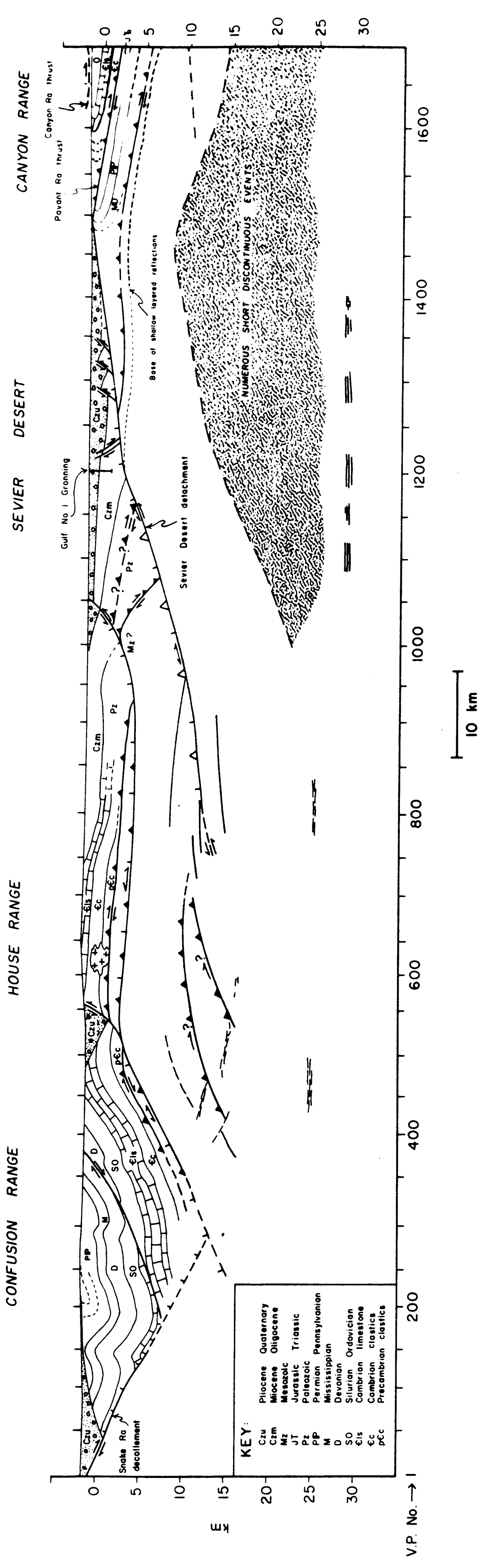

Figure 3. Preliminary depth section, with surface geology, constructed along route of COCORP line 1. This section removes velocity effects inherent in time section. Sawteeth = thrust faults; ticks = low-angle normal faults; sawteeth with ticks = thrust reactivated as normal fault; open sawteeth with tick = low-angle normal fault, uncertain if reactivated; pluses = Jurassic pluton in House Range.

upper Cenozoic sediments of the Sevier Desert basin do not cut the detachment surface. Those normal faults are clearly identifiable on the seismic sections where they displace a strong reflection from a 4.2 ± 0.3-m.y.-old basalt (Lindsey et al., 1981) (see event B at VPs 1230 and 1285, Fig. 2). Thus, the Sevier Desert detachment must have undergone extensional displacements in a down-to-the-west sense at least as recently as the Pliocene. The amount of those displacements, based on possible hanging-wall and footwall cutoffs discussed below, may lie between 30 and 60 km.

The multicyclic character of reflection A may represent reflectivity zone of finite width (0.1–0.5 km thick); reverberation within a wide zone of brecciation and hydrothermal alteration might produce the observed cyclicity. Alternatively, the cyclic events could correspond to sedimentary layering as implied by Mitchell (1979). In this latter case the fault could be a reactivated thrust that is located at the top of the band of events.

The extent of the detachment west of VP 800 and deeper than 5 s (12–15 km) is less certain. A series of westward-steepening reflections underneath VPs 800–350 and between 4 and 7 s (11–20 km) coincide with or splay off the western end of the Sevier Desert detachment (events C, Fig. 2). The general geometry of these events resembles a zone of imbrication and thickening over thrust ramps. A ramp in this position would explain the 10 km of pre-Oligocene structural relief observed between the House and Confusion Ranges (Hose, 1977; Hintze, 1974) and is similar to Armstrong's (1982) model for the region. If correct, this interpretation suggests that Mesozoic thrusts penetrate to within 10 km of the present base of the crust. Alternatively, the features may represent the transition from a single, dominantly brittle detachment to a zone of more distributed ductile shearing during extension. This latter interpretation is favored by the spatial association with the westernmost and deepest part of the Sevier Desert detachment.

Shallower Cenozoic and Mesozoic Detachments

Below and east of the Sevier Desert detachment, event D (Fig. 2), at about 1 s (2.5 km) at the east end of the line, is probably related to the east-dipping and east-verging Pavant Range thrust. This correlation is based on the position of D near the base of the Cambrian and on the northward subsurface projection of structures exposed south of the line. The structurally higher Canyon Range thrust projects in the air above the COCORP line. Prominent reflections at 2–2.5 s (5–6 km, event E, Fig. 2) may be from structurally lower Mesozoic thrusts that are inferred in the subsurface from industry data beyond the east end of the line. The position of the sedimentary rock-crystalline basement interface anywhere on line 1 is uncertain.

Correlation of structures on either side of the Sevier Desert detachment is critical for determining displacements on the detachment as well as for demonstrating whether the detachment is a single reactivated Mesozoic thrust, a reactivation of several Mesozoic thrusts, or a new Cenozoic fault. Event F (Fig. 2) can be traced from VP 400 to VP 980, and may extend farther east to a hanging-wall cutoff on the Sevier Desert detachment at VP 1070. A somewhat less continuous event, G, can be traced from VP 560 eastward to where it appears to "pinch out" against F beneath VP 900.

Cenozoic normal faults at VP 560 along the west side of the House Range and at VP 1050 sole into or are truncated by event F (Fig. 2), showing that F has apparently accommodated Cenozoic extension. However, projection of mapped surface units with known thicknesses (Hintze, 1974; Hose, 1977) to depth suggests that both events F and G parallel bedding over most of their lengths (50 km for F). Most new Cenozoic detachments do not parallel upper-plate bedding for such distances, suggesting that F is a pre-existing surface, either a stratigraphic horizon or a Mesozoic thrust, or both. G is probably cut by the normal fault at VP 560 and could also be bedding and/or a thrust. A comparison of Cambrian stratigraphy in the House and Pavant Ranges (Hintze, 1973) suggests that the Pavant Range thrust is in the subsurface beneath the House Range; the stratigraphic and structural levels of F and G indicate that they could be correlated with the Pavant and Canyon Range thrusts, respectively. Those correlations suggest 50–60 km of extension on the Sevier Desert detachment; a minimum extension of 30 km is required by the inferred position of the Pavant thrust beneath the House Range. Finally, F could be a thrust-duplicated equivalent of event A, a possibility easier to visualize if both events correspond to lithologic horizons rather than structural surfaces. Even in this last possibility, normal fault displacements are the most recent movements on, or just above, both A and F.

Snake Range "Decollement"

Event H, a prominent band of reflections in the zone of few events between VPs 1 and 340 (Fig. 2), has a gentle east dip and projects to the surface at the approximate position of the Snake Range decollement that crops out just off the west end of the line (Fig. 1). Event H can be traced eastward only as far as VP 200 and as deep as 3 s (8 km). Thus, the seismic data do not resolve the relations between the Snake Range decollement and the previously described structures that occur farther east. Industry reflection data (Smith, 1982) and faint line-ups on the COCORP section suggest that event F may extend well west of the axis of the Confusion Range synclinorium to considerable crustal depths (Figs. 2, 3). If so, then the latest movement on F probably postdates and truncates the Snake Range decollement.

An important change in vergence of Cenozoic structures occurs at the axis of the Confusion Range synclinorium. To the west, Cenozoic upper-plate motion on the upper plate of the Snake Range decollement was eastward relative to the lower plate, but to the east the upper plates of two detachments, A and F, moved west relative to their lower plates during the Cenozoic. This suggests either a diachronous regional evolution of low-angle extensional structures or more absolute extension (due to ductile stretching or igneous intrusion) in the lower crust than in the upper crust.

Deep Reflections

On the western two-thirds of the line (VPs 430–520, 770–820) the deepest reflections are two- or three-cycle events that occur between 9.0 and 9.5 s (about 25–30 km depth) (I, Fig. 2). These events fall in the depth range of the crust-mantle transition defined by wide-angle reflections from a seismic-refraction experiment (Smith, 1978). At the east end of the line between VPs 1000 and 1650 (Fig. 2), the lower crust appears to be characterized by a wedge-shaped zone of numerous discontinuous reflections, the upper surface of which tends to parallel shallower structures. The depth section (Fig. 3) shows that this parallelism is not an effect of velocity pull-ups. The diffuse western tip of the wedge-shaped zone coincides in time with events I farther west (Figs. 2, 3). Apparently, broad-scale geometries in the lower crust conform to or parallel in a general way major structures shallower in the crust. The coincidence of the wedge-shaped zone with a Bouguer gravity high, Quaternary basalts, and high heat flow within the eastern part of the Sevier Desert (Smith, 1978), indicates that it may be related to recent extensional processes.

The deepest events on line 1 between VPs 1100 and 1400 are very prominent three-cycle events that occur in a discontinuous band between 10.5 and 11.5 s (about 30 km) (Fig. 2). The longer travel time under the thickest section of Cenozoic sediments in the Sevier Desert basin suggests a velocity pull-down effect. Cross line 5 and analysis of parallel offset segments of line 1, south of Delta (Fig. 1) indicate that the events are directly beneath the line and are not energy from out of the plane of the section. Thus, at about 30 km depth, these cyclic events occur below the transitional Moho determined by refraction data to lie at 25 km. A particularly striking feature of line 1 is that whereas middle- and lower-crustal features have moderate dips, the deepest events when corrected for velocity effects are nearly flat. This geometry gives the impression of crustal features truncated at or near the base of the crust and suggests a complex evolution of the Moho, perhaps during both the Mesozoic and the Cenozoic.

CONCLUSIONS

The striking lateral continuity of the features imaged on COCORP line 1 and on industry reflection data (McDonald, 1976; Smith, 1982) forces a re-evaluation of classical Basin and Range models and raises important questions about pre–Basin and Range tectonics of the region. Preliminary conclusions based on the first phase of COCORP profiling in west-central Utah include the following: (1) High-angle normal faults known in the near surface do not extend deep into the crust but instead are either truncated or sole into regional low-angle detachments, some with perhaps many tens of kilometres of Cenozoic displacement. (2) Three discrete Cenozoic detachment surfaces (A, F, H) are interpreted. Though ductility of the individual fault zones probably increases with depth, the detachments do not merge into a single subhorizontal zone of decoupling at upper- or middle-crustal levels. The geometry of individual detachment horizons resembles Wernicke's (1981) model, at least in the upper 15 km of the crust. (3) Mesozoic thrust faults (D, C?, E?, F?, G?) may be traced westward to considerable crustal depths, showing consistent relations to major structures exposed at the surface. Although Cenozoic reactivation of thrusts is reasonable for at least some low-angle faults (F), it remains uncertain whether two major Cenozoic detachments (A, H) are reactivated or not.

While these observations provide critical resolution on the effects of Cenozoic extension, the mechanics of that extension remain enigmatic. Pulling the crust apart on very low-angle faults would appear mechanically impossible, yet the COCORP data presented here and a growing number of field studies over the past several years (articles in Crittenden et al., 1980; articles in Frost and Martin, 1982) provide impressive evidence that such extension does occur.

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Reviewer's comment

The seismic reflection data described here are some of the most tantalizing seen yet in the COCORP program.

Gregory Davis

Fig 2, p. 1 of 2

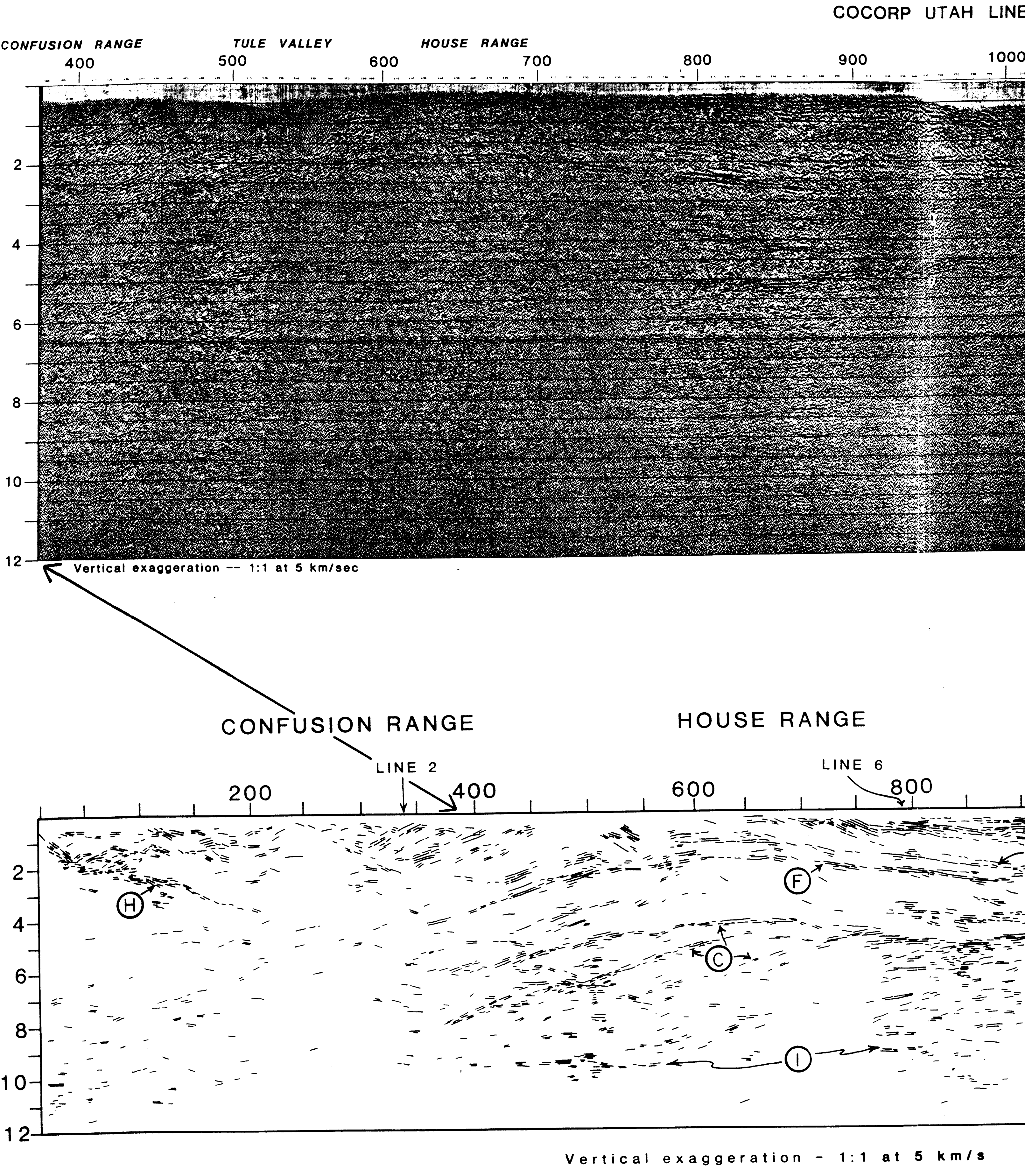
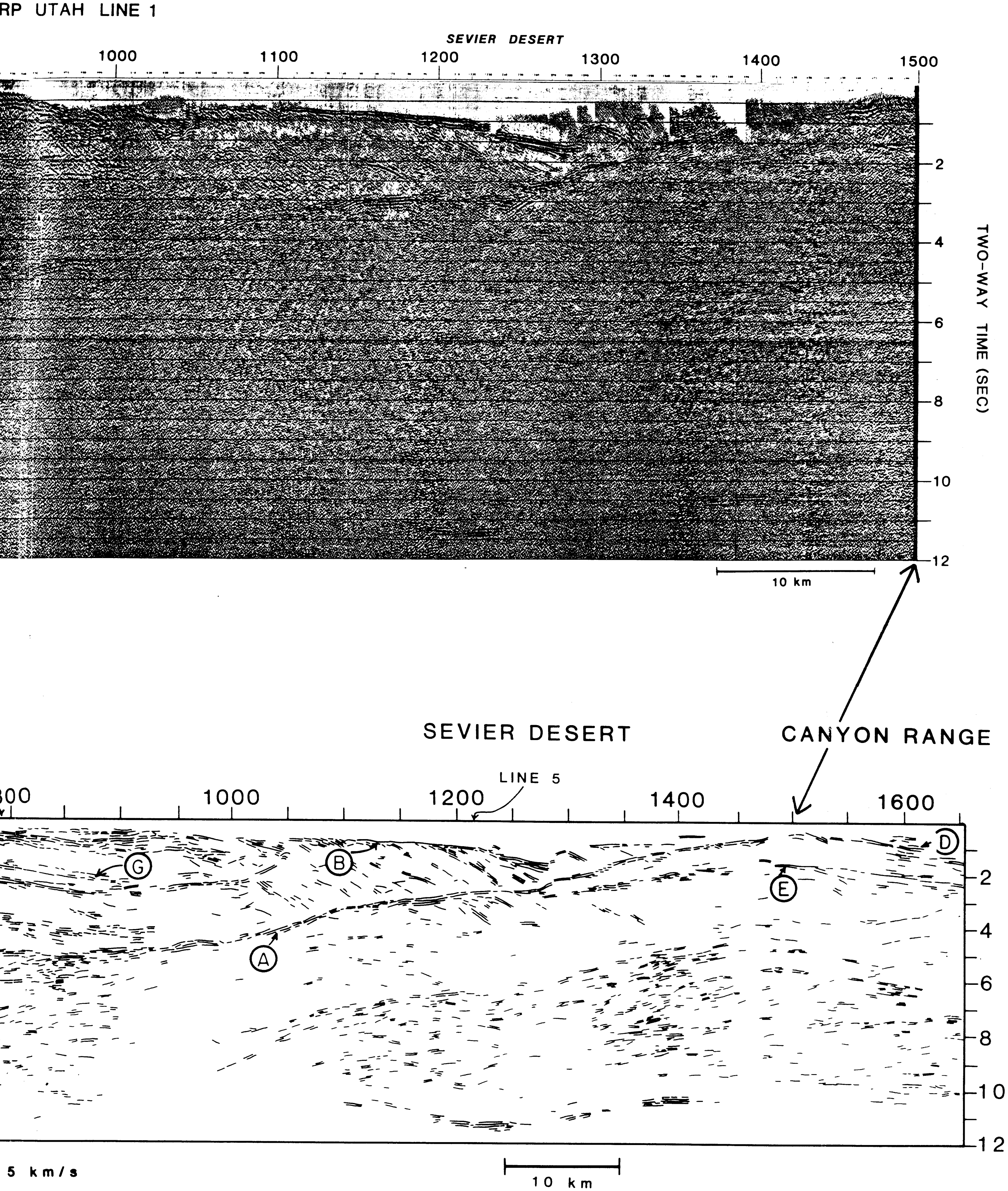


Figure 2. Upper: COCORP line 1 between VPs 375 and 1500. These sections have
migrated or deconvolved. Lower: line drawing abstracted from all of COCORP line 1.
tinuity of events A, C, and F.



hese sections have automatic gain control (AGC) window of 1 s and are not
of COCORP line 1. Letters refer to features discussed in text. Note lateral con-