Is the Sevier Desert reflection of west-central Utah a normal fault?

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ABSTRACT

A prominent west-dipping reflection that can be traced in seismic-reflection profiles over an area of 7000 km² beneath the Sevier Desert basin of west-central Utah is generally referred to as the Sevier Desert detachment and is widely regarded as one of the best examples of an upper-crustal low-angle normal fault. The absence of evidence for fault-related deformation in drill cuttings and core from two industry boreholes that intersect this feature casts doubt on the fault interpretation. The existing interpretation is based mainly on the observation that high-angle normal faulting is restricted largely to Tertiary sedimentary and volcanic rocks above the reflection. An alternative explanation is that the high-angle faults are related to the withdrawal of early deposited lacustrine salt, which even today is as much as 2 km thick. Reevaluation of the seismic data suggests that the Sevier Desert reflection consists of two spatially and genetically distinct segments: a shallow segment here interpreted as an unconformity between Paleozoic and Tertiary strata and a fortuitously aligned deeper segment that is traceable to mid- and lower-crustal levels and that appears to represent a thrust fault related to the Cretaceous Sevier orogeny.

INTRODUCTION

The geologic community is divided as to whether normal faults with dips of <20° can be active in the upper crust (Wernicke, 1981, 1992; Allmendinger et al., 1983; Axen, 1993; John and Foster, 1993) or whether they form at high angles and are subsequently rotated to lower angles during continued deformation (Davis, 1983; Spencer, 1984; Buck, 1988; Hamilton, 1988; Wernicke and Axen, 1988). Jackson (1987) studied a large number of earthquake focal mechanisms from normal faults and concluded that none could be attributed confidently to slip on low-angle structures. Abers (1991) interpreted a single earthquake in eastern Papua New Guinea in terms of slip on a subsurface continuation of a detachment fault associated with a metamorphic core complex in the D'Entrecasteaux extensional province, but his conclusions are equivocal. Sibson (1985) argued that the frictional resistance of an upper-crustal low-angle normal fault is too great to permit movement. In contrast, Axen (1992) suggested that frictional resistance might be overcome under conditions of elevated pore-fluid pressure (cf. Scholz, 1992). Recognizing the apparent paradox of upper-crustal normal faulting, several authors have concluded that low-angle normal faults develop in the upper crust only under special conditions (e.g., Forsyth, 1992; Parsons and Thompson, 1993) and that, unless these conditions exist, extension is accommodated by high-angle normal faults, with dips flattening only below the brittle-ductile transition region (e.g., Miller et al., 1983; Lister and Davis, 1989; Melosh, 1990; Lister and Baldwin, 1993).

Commonly cited as evidence in support of the notion that slip can take place on upper-crustal low-angle normal faults is a prominent reflection observed in seismic-reflection profiles across the Sevier Desert basin of west-central Utah (Fig. 1). The reflection, which dips westward at about 11° and can be traced in seismic data over an area of 7000 km², was first interpreted as a detachment fault by McDonald (1976), and this idea has been accepted in subsequent studies (Wernicke, 1981, 1985; Allmendinger et al., 1983, 1985; Von Tish et al., 1985; Planke and Smith, 1991) despite the fact that the "fault" is everywhere buried beneath the Sevier Desert basin. According to McDonald (1976), the reflection corresponds to a Sevier-age (Cretaceous) thrust decollement that subsequently underwent backsliding of the hanging wall after the cessation of shortening, a process that has been shown to have taken place in the nearby Wyoming segment of the thrust belt (Lamerson, 1982; West, 1992). Wernicke (1981, 1985) used the Sevier Desert reflection as a model for the early stages of unroofing of metamorphic core complexes, in which the hanging wall slides back on a flat surface, breaks into a series of domino-style blocks and exposes mid-crustal rocks of the footwall. On the basis of seismic data acquired by COCORP (Consortium for Continental Reflection Profiling) in the early 1980s, and in contrast to McDonald (1976), Allmendinger et al. (1983) and Von Tish et al. (1985) concluded that the normal faulting was not influenced by the location of Sevier thrust faults. By matching apparently offset features in hanging-wall and footwall blocks, they estimated that as much as 38 km of displacement had occurred on the supposed detachment since the late Oligocene. Planke and Smith (1991) obtained a significantly smaller estimate of 5.5 to 7.2 km by dividing the cross-sectional area of the Sevier Desert basin by the maximum depth (12 to 15 km) to which the reflection can be traced. Unfortunately, the assumption of mass balance implied in the technique they used is not maintained. Thus, if the fault interpretation is correct, the best estimate of displacement remains that of Von Tish et al. (1985), and this is the one addressed in this paper.

All of these interpretations were based mainly on the fact that, in the seismic-reflection data, high-angle normal faulting is largely restricted to Tertiary sedimentary and volcanic rocks above the reflection; few if any of these faults appear to offset the reflection itself. However, none of the published interpretations involved direct observation of the supposed detachment surface. New evidence summarized in this paper now casts doubt on the fault interpretation and indicates that over large areas the reflection may instead be due to an unconformity.

LOCATION OF THE SEVIER DESERT REFLECTION IN BOREHOLES

In considering the origin of the Sevier Desert reflection, perhaps the most important issue concerns the precise correlation of the reflection to the geology encountered in available boreholes. Over large areas, the reflection appears to correspond to the Paleozoic-Tertiary contact, a surface that is associated with a marked change in acoustic impedance (the product of density and seismic velocity). The fault interpretation can therefore be tested by examining this contact, as long as the sites chosen exclude the possibility of intersecting rider blocks of Paleozoic rocks that might locally be present above a detachment fault. The Sevier Desert reflection is penetrated by a number of boreholes drilled in the course of oil and gas exploration in the late 1970s and early 1980s (Sharp, 1984; Planke and Smith, 1991). Recently, we obtained cuttings and core from the ARCO Hole-in-the-Rock and ARCO Meadow Federal #1 exploration wells (AHR and AMF #1), courtesy of ARCO. In both holes, the boundary is marked by a sharp decrease in the proportion of sandstone plus siltstone (Tertiary) and by a concomitant increase in the proportion of Paleozoic carbonate, which tends to be fossiliferous and oolitic (Fig. 2). The persistence of sandstone and siltstone in cuttings below the contact is attributed to caving. Sonic logs from the two boreholes reveal a marked increase in seismic velocity (and

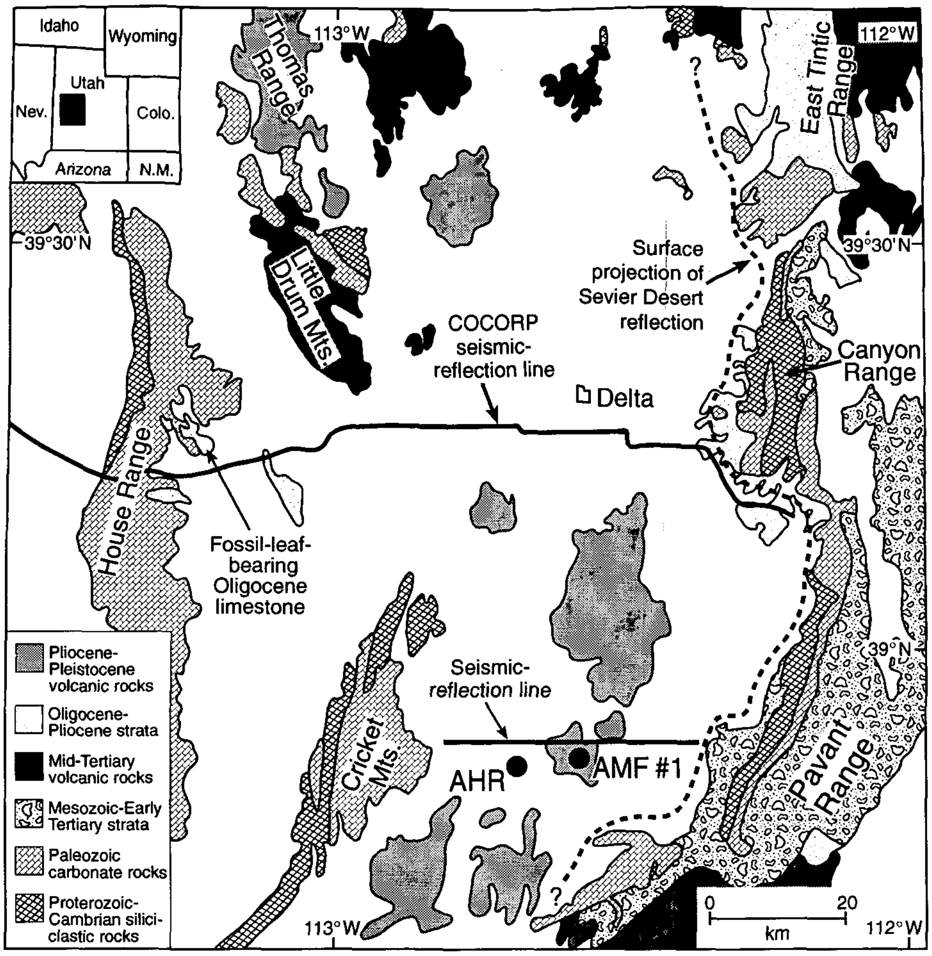


Figure 1. Generalized geologic map of Sevier Desert basin area, not including faults, modified from Allmendinger et al. (1983) and Planke and Smith (1991). Circles denote locations of two industry boreholes: ARCO Hole-in-the-Rock (AHR); and ARCO Meadow Federal #1 (AMF #1). Seismic-reflection line from Planke and Smith (1991). COCORP seismic-reflection line from Allmendinger et al. (1983).

thus acoustic impedance) at the same horizon, confirming the inferred correlation with the seismic-reflection data. In AMF #1, the velocity increases abruptly downward from 4.7 km/s to 5.9 km/s. In AHR, it increases from 4.9 km/s to 6.4 km/s at the contact and then gradually increases over 35 m to 6.8 km/s.

ABSENCE OF BRITTLE DEFORMATION

Studies of microfracturing in sandstones near faults (e.g., Brock and Engelder, 1977; Anders and Wiltschko, 1994) have shown that microfracture density increases significantly within 3 m of a fault surface even for normal faults displaced as little as 2 m. A pronounced increase in microfracturing would, therefore, be anticipated close to a fault with tens of kilometres of displacement. Thin sections of a series of samples recovered at 3 m intervals from the AHR and AMF #1 boreholes were used to evaluate the level of deformation close to the Paleozoic-Tertiary contact. Microfracture density was assessed by using the microfracture index developed by Borg et al. (1960). In this technique, all microfractures are counted in 10 to 20 quartz grains per chip and in 18 chips per sampling interval. Grains are selected to be of approximately uniform size, and microfractures are counted with the same microscope ocular, because the assessment of microfractures is obviously influenced by grain size and magnification. Individual grains are binned according to the number of microfractures that they contain, on a scale that ranges from 100 (no microfractures) to 500 (totally smashed grain). For example, a microfracture index of 250 for a given sampling interval implies that, on average, each grain in the sample contains seven microfractures. In their study of the Muddy Mountains thrust of southern Nevada, a fault of large displacement but with a relatively narrow fault zone, Brock and Engelder (1977) determined a microfracture index of 250 from samples taken from within 3 m of the fault. The microfractures used in our study are "healed" or "partially healed" microfractures (see Kranz, 1983), features that are easily distinguishable from fractures induced by drilling.

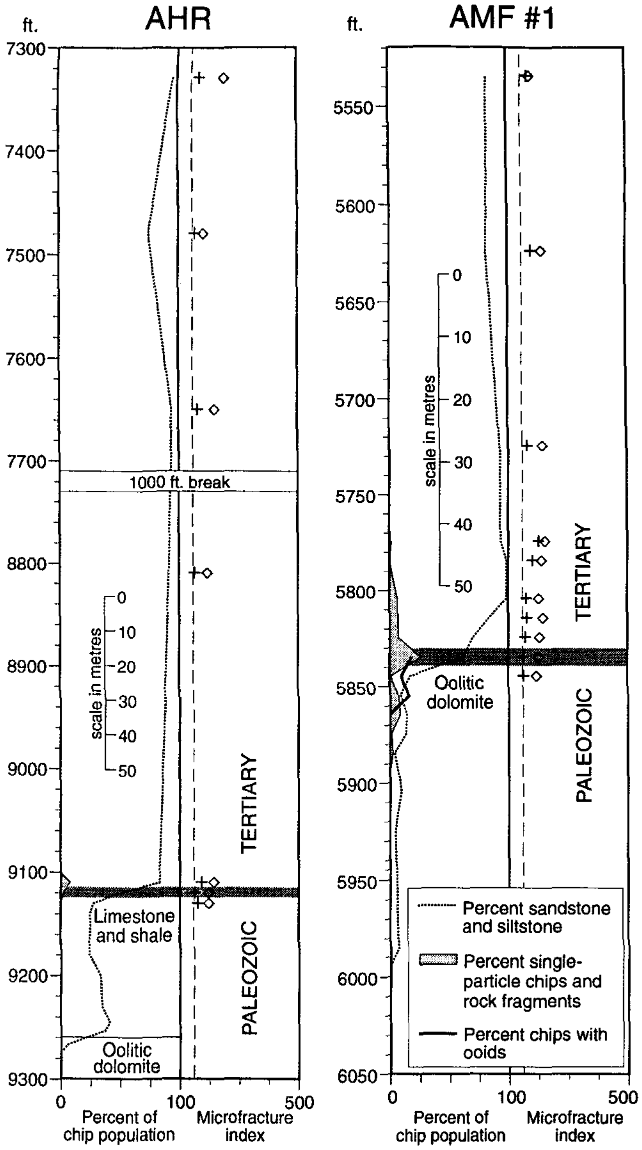
Contrary to expectation, the microfracture index does not vary significantly with depth, and if anything decreases slightly as the Paleozoic-Tertiary contact is approached in both boreholes (Fig. 2). No smashed grains, angular fragments, or other signs of cataclasis are observed. Many grains within the siltstone and sandstone chips are characterized by undulose extinction, and in general the abundance of such grains increases downhole toward the contact, especially in AMF #1. However, the fact that this trend is not matched by a corresponding change in the density of microfracturing indicates that the undulose extinction is inherited from an earlier deformational event, presumably the Sevier orogeny, and that the observed variation in the abundance of undulose grains is due solely to a change in provenance. Given that the present depth to the contact is the maximum depth of burial predicted by any of the faulting models, plastic deformation of quartz could not have taken place during the late Tertiary under any plausible geothermal gradient (Borg et al., 1960; Griggs et al., 1960). We conclude that the absence of significant deformation and the lack of variation in deformation in the vicinity of the Paleozoic-Tertiary contact is not consistent with the existence of a fault with tens of kilometres of displacement. This is especially the case because the present geometry of blocks in the hanging wall of the supposed detachment implies significant beveling and cataclasis during displacement to accommodate an obvious space problem that arises in palinspastic reconstruction (see Sharp, 1984; Von Tish et al., 1985).

OTHER EVIDENCE THAT CONFLICTS WITH EXISTING INTERPRETATIONS

Undeformed Ooids and Fossil Fragments

Samples of Paleozoic carbonate rocks recovered from within 12 m of the contact with Tertiary sandstone in the AMF #1 borehole contain undeformed ooids (see Kerr, 1993, for photomicrograph). A sample of limestone recovered in core from 15 m below the Paleozoic-Tertiary contact in borehole AHR contains undeformed trilobite fragments. The main expression of deformation is the presence of releasing-bend microfaults, features interpreted by Ferrill and Groshong (1993) to be characteristic of depths of deformation <2.4 km. In the detachment interpretation, Paleozoic rocks of the lower plate would have been at a depth of about 7 to 8 km at the time faulting began, and, given a plausible geothermal gradient, confining pressure, and strain rate, they should have

Figure 2. Four columns representing percent of total chip population and microfracture index in vicinity of Paleozoic-Tertiary contact in ARCO Hole-in-the-Rock (AHR) and ARCO Meadow Federal #1 (AMF #1) boreholes (see Fig. 1 for location). Depth is in feet from on-site driller's log. Sampling interval for cuttings is 10 ft (~3 m). Depth marks indicate middle of sampling interval. Horizontal shaded interval represents position of Paleozoic-Tertiary contact. Microfracture index is from Borg et al. (1960), where 100 represents zero microfractures per quartz grain and 500 represents all quartz grains as smashed (see text for further discussion). Crosses indicate microfracture index for quartz grains without undulose extinction, and diamonds indicate index for quartz grains exhibiting undulose extinction. Dashed reference line represents microfracture index for nonundulose quartz grains found in interval containing Paleozoic-Tertiary contact.



been ductilely deformed (Handin et al., 1960; Donath et al., 1971).

Paleoelevation of the Supposed Hanging Wall

Another piece of evidence that is difficult to accommodate in the fault interpretation is provided by freshwater lacustrine limestone of mid-Oligocene age that crops out in the House Range, along the western margin of the Sevier Desert basin in the assumed hanging-wall block (Fig. 1). The limestone contains gastropod shells (*Helix* and *Lymnaea*) and fossil leaves from poplar and willow trees (Hintze, 1981). In the palinspastic reconstruction of Sharp (1984) and Von Tish et al. (1985), rocks in the hanging wall are restored to an elevation as much as 7 km (23,000 ft.) higher than rocks that are today at about the same elevation in the footwall. Alluvial conglomerate of early Oligocene age (>32 Ma; Campbell, 1979) that crops out in the Canyon Range in the footwall block must have been deposited above sea level. So no matter what assumptions are made about isostatic compensation, the reconstruction implies that the limestone accumulated at an elevation higher than might be expected for the associated flora (K. M. Gregory, 1994, personal commun.). This difficulty can be resolved only if the total displacement on the inferred detachment is considerably less than the maximum 38 km proposed by Sharp (1984) and Von Tish et al. (1985).

AN ALTERNATIVE HYPOTHESIS

In view of these difficulties, and elaborating on ideas presented by Anders (1993), we propose an alternative interpretation for the Sevier Desert reflection, one that does not involve displacement along this feature during Tertiary time. We suggest that the reflection consists of two spatially and genetically distinct segments that are fortuitously aligned. The main segment is thought to correspond to an unconformity at which Tertiary sedimentary rocks rest in depositional contact on Paleozoic rocks. A second, deeper segment, observed only in the northern part of the Sevier Desert basin, appears to branch into several splays and is offset from the upper reflection. These splays are traceable to mid- and lower-crustal levels and may represent mylonite zones of Sevier age. Located above the lower reflection is an anticline, which we interpret as a ramp anticline associated with Sevier-aged thrusting (see Fig. 2 of Allmendinger et al., 1983).

The existence of an unconformity is supported by evidence for a basal conglomerate. In cuttings of uniform chip size, the proportion of chips composed entirely of a single particle of quartz, feldspar, quartzite, or volcanic rock fragments ought to reflect the grain size of the rocks from which the chips were derived. The fact that the abundance of single-particle chips increases downward toward the Paleozoic-Tertiary contact (see borehole AMF #1 in Fig. 2) indicates a pronounced increase in grain size, in contrast to the decrease in grain size that might be anticipated if a fault were present (e.g., Brock and Engelder, 1977).

If the Sevier Desert reflection is due to the presence of an unconformity, it is necessary to explain the lack of significant offset by high-angle normal faults above it. The most reasonable possibility is that the high-angle faults are for the most part due to withdrawal of early deposited salt. The style of deformation is similar to that observed at passive continental margins known to be underlain by thick salt deposits (Harding and Lowell, 1979; Bally, 1983). One of the boreholes in the Sevier Desert basin penetrated a section of salt as much as 2 km thick (Planke and Smith, 1991) and several features observed in seismic sections can be interpreted as velocity pullups (see the central part of section #8 of McDonald, 1976).

CONCLUSIONS

Borehole samples obtained from levels close to the depth of the Sevier Desert reflection in west-central Utah exhibit no significant fault-related deformation, and this casts doubt on the widely held view that the reflection represents a regional detachment fault with as much as 38 km of displacement. Reevaluation of the seismic data suggests that the reflection consists of two distinct segments, the most important of which is an unconformity between Paleozoic and Tertiary strata. This alternative hypothesis can be tested by means of scientific drilling in the Sevier Desert basin.

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