Reanalysis of the COCORP Utah Line 1 deep seismic reflection profile: Toward an improved understanding of the Sevier Desert detachment question

John H. McBride1,*, William J. Stephenson2, and Eleanor I. Prussen McBride1
1Department of Geological Sciences, Brigham Young University, P.O. Box 24606, Provo, Utah 84602, USA
2U. S. Geological Survey, Box 25046, MS 966, Denver, Colorado 80225, USA

ABSTRACT

The Sevier Desert detachment (or “reflection,” SDR), which underlies the Sevier Desert basin along the eastern margin of the USA Basin and Range, is commonly cited as a “type example” of a low-angle normal fault (LANF) in continental crust. We present the results of reanalyzing the SDR on the COCORP (Consortium for Continental Reflection Profiling) deep seismic profile crossing the Sevier Desert basin (Utah Line 1). We employ a strategy of showing how shallow crustal velocity models, derived from first-break analysis of the shot records, may be used to reduce the effect of lateral velocity variations on imaging the SDR. Our results imply that the irregularities and discontinuities along the SDR are likely caused by overlying lateral velocity variations. The reprocessed versions of the section reveal a smoother, simpler, and more continuous SDR, lacking most of the apparent large offsets and structural variations on the currently available version of the profile. Seismic attribute and structural analyses of the reflection indicate significant variations along the profile, which are likely related in part to the field acquisition, but may also suggest lateral variations in the physical origin of the SDR. Such lateral variations may be consistent with previous studies that challenge the LANF interpretation of the SDR on the basis of attributing different origins to different parts of the reflector; however, a smoother and more continuous SDR points to a tectonically uniform origin and is thus interpreted to be more consistent with a LANF explanation.

INTRODUCTION

Understanding the mechanism of low-angle-normal-fault (LANF) formation remains an enduring puzzle in earth science. One of the most oft-cited examples of a continental LANF is the Sevier Desert reflection (SDR) or “detachment,” along which crustal extension has purportedly been accommodated in the eastern Basin and Range in west-central Utah, USA (Allmendinger et al., 1983; Smith and Bruhn, 1984; Von Tish et al., 1985; Planke and Smith, 1991; Coogan and DeCelles, 1996; Carney and Janecke, 2005; DeCelles and Coogan, 2006) (Figs. 1 and 2). The SDR has achieved a sort of iconic status as one of the type examples of a LANF that developed in continental crust (e.g., Wernerick, 1981; Coleman and Walker, 1994). However, the validity of the detachment interpretation for the SDR has been discussed at length in the literature (Mitchell and McDonald, 1986; Allmendinger and Royse, 1995; Anders et al., 1995, 1998; Wills et al., 2005; Christie-Blick and Anders, 2007; Coogan and DeCelles, 2007; Christie-Blick et al., 2007a). The leading alternative interpretation is that the SDR represents a shallow crustal unconformity aligned with a deeper Mesozoic thrust fault (Anders and Christie-Blick, 1994). A key data set for interpreting the SDR is the COCORP (Consortium for Continental Reflection Profiling) Utah Line 1 deep seismic reflection profile (Fig. 2), acquired in 1982. Despite the intense focus on the SDR, relatively little interest has been shown in the actual seismic reflection data set itself, with most studies (but see also Smithson and Johnson [1989]) citing the original early 1980s version of the data (Allmendinger et al., 1983; Von Tish et al., 1985). For example, recent papers by Christie-Blick et al. (2007a), Hintze and Davis (2003), and Niemi et al. (2004) reproduce the travel-time section or a line drawing of it. Yet, the expression of the SDR on the originally processed common-depth-point (CDP) seismic profile is far from simple. Key geophysical factors that might be used to challenge the detachment origin include the poor continuity of the SDR, apparent changes in reflection character, variations in structural slope, and apparent offsets or major structural irregularities of the reflection. Previous workers have not necessarily misinterpreted such features, but the unavailability of a depth section for the actual seismic data may present a hindrance to pursuing a more detailed interpretation of the SDR. The purpose of this paper is to, first, present the results of a reprocessing effort, highlighting the sources of the distortion of the seismic image. From a purely technical point of view, we wished to test the hypothesis that applying a static correction based on a two-layer velocity model derived from first-break analysis would smooth and simplify the expression of the SDR. Second, we demonstrate the use of seismic attributes in order to examine continuity and consistency of the SDR. Last, our study does not seek to settle the debate on the SDR, but to suggest how the new results refocus some issues for the controversy of the detachment interpretation beneath the eastern Basin and Range. As part of our presentation, we assess the limitations of the methodologies, which are important due to varying subsurface and attenuation conditions, to the limited frequency bandwidth of the seismic data, and to the lack of good seismic velocity control along the profile.

*Corresponding author e-mail: john_mcbride@byu.edu.

Geosphere; December 2010; v. 6; no. 6; p. 840–854; doi: 10.1130/GES00546.1; 8 figures.
Figure 1. Geologic map (prepared from digital data in Hintze et al. [2000]) for the Sevier Desert basin area. Faults are shown as black solid lines (including faults from the Quaternary fault and fold database of the U.S. Geological Survey [U.S. Geological Survey, 2006]). Geologic units are coded: Q—Quaternary; T—Tertiary; K—Cretaceous; J—Jurassic; Tr—Triassic; P1 and P2—Permian; PP—Pennsylvanian–Permian; P—Pennsylvanian; M—Mississippian; D—Devonian; S—Silurian; O—Ordovician; C—Cambrian; PC—Precambrian. The reader is directed to Hintze et al. (2000) for further explanation of the symbols. Selected parts of the map are labeled with unit symbols. Selected volcanic rock outcrops are noted. The location of the reprocessed COCORP profile is shown by CDP numbers (green dots) and the vibrator point locations by squares. A more detailed version of a portion of the area shown in the map, including the interpretation of faults, is provided by Hintze and Davis (2002).
GEOLOGICAL AND GEOPHYSICAL BACKGROUND

The Sevier Desert basin in west-central Utah, USA, resulted from Cenozoic crustal extension superimposed over the older, late Mesozoic–Eocene structure of the Sevier fold-and-thrust belt (Planke and Smith, 1991; Hintze and Davis, 2003). The basin is bordered on the east and west by the Paware and Canyon ranges and the Cricket Mountains, respectively, and is filled with 4.0 ± 0.6 km of sedimentary strata that thicken to the west (Planke and Smith, 1991) (Fig. 1). Post-Sevier Orogeny erosion is expressed locally by early Cenozoic continental sediments that overlap Cretaceous and early Tertiary synorogenic strata (Hintze and Davis, 2003). Widespread volcanic deposits of

Figure 2. (A) the unmigrated stacked section for the eastern portion of the COCORP Utah Line 1 profile displayed with the original data processing (the digital data are available publicly from Cornell University as a SEG-Y file). Only the first 6 s of traveltime are displayed. The CDP numbers are from the original processing performed at Cornell University. The exact locations of the CDPs are not available, and do not match those from the present reprocessing as shown in Figure 1. Vibrator point locations (VP) are also shown (see Fig. 1) as taken directly from the printed section (Nelson, 1988). For this and all seismic sections, 0 traveltime represents the processing datum of 1900 m above sea level, except as noted otherwise. (B) migrated section from Von Tish et al. (1985). Yellow dashed line traces the interpreted SDR. AAPG©1985, reprinted by permission of the AAPG whose permission is required for further use. (C) simplified redrawing of preliminary depth section of Allmendinger et al. (1983) showing only their interpretation of the SDD and associated reflectors. On this cross section we plot the approximate correspondence of the CDPs from the reprocessed section (Fig. 4) and the VPs (projected perpendicular to the CDP profile) so that the previous sections can be compared with the reprocessed versions.
variable thickness began to accumulate in the basin beginning in the middle Eocene and are likely related to the episode of crustal extension (Hintze and Davis, 2003). Recent tectonism is evidenced by Holocene faulting (Fig. 1) that is mapped in the vicinity of the COCORP profile; some of the more prominent faults (e.g., the Holocene Clear Lake fault [Hintze and Davis, 2003]) may be projected into the profile. The area along the seismic profile where the SDR appears (approximately the central part of the eastern half) traverses only Quaternary surficial Lake Bonneville deposits (Fig. 1) and thus outcrop constraints for interpreting subsurface reflections are lacking.

The Sevier fold-and-thrust belt is one of the most studied fold-and-thrust belts in the world and constitutes a transitional zone located just west of the Basin and Range–Colorado Plateau boundary (e.g., Burchfi el and Davis, 1975; Planke and Smith, 1991; Hodges and Walker, 1992; Wernicke, 1995; DeCelles and Coogan, 2006). However, understanding the preextensional history of this region requires that one first understand the amount of extension that may have displaced Sevier-aged and older structures (DeCelles and Coogan, 2006). In particular, DeCelles and Coogan (2006) have argued that “large-magnitude extensional restoration” is required along Sevier thrust faults in order to maintain a critical taper commonly observed in fold-and-thrust belts throughout the world. Interpretations of industry and academic seismic reflection profiles from the Sevier Desert basin have suggested a regional detachment (“Sevier Desert detachment”) that extends for over 70 km beneath the basin and to the west to the Utah–Nevada border (Allmendinger et al., 1983; Smith and Brunn, 1984; Von Tish et al., 1985; Planke and Smith, 1991) (Fig. 2). Planke and Smith (1991) give estimates of at least 80-130 km for the north-south width of the interpreted detachment. Palinspastic restoration has been used to suggest that the total horizontal displacement on the interpreted detachment lies between 28 and 38 km (Sharp, 1984; Von Tish et al., 1985) or more (Coogan and DeCelles, 1996). Further review of the stratigraphic, structural, and tectonic background of the Sevier Desert basin can be found in Hintze and Davis (2003), Wills et al. (2005), and DeCelles and Coogan (2006).

THE SEVIER DESERT REFLECTION INTERPRETED AS A DETACHMENT

The Sevier Desert detachment is not exposed in outcrop and is inferred to exist almost entirely on the basis of seismic reflection profiles (mostly 1970s vintage data [Hintze and Davis, 2003]). The break-away zone for the detachment has been suggested to be along the western side of the Canyon Range (e.g., Otton, 1995) (Fig. 1), although this has been disputed (Wills and Anders, 1999) (see also review in Morris and Hébertson, 1996). Although numerous petroleum industry seismic profiles have been used to describe the detachment, most of these only show the detachment as a subhorizontal boundary in the shallow sedimentary crust (Planke and Smith, 1991; Coogan and DeCelles, 1996; Wills et al., 2005). The COCORP Utah Line 1 (Fig. 2) deep seismic data set provides the only profile with a broad, full-crustal-scale perspective (Smith and Brunn [1984] show an ~5 s seismic industry profile that approximately follows the COCORP profile). Thus the debate on the meaning of the reflector tends to pivot on the single COCORP profile.

METHODOLOGY: REPROCESSING OF COCORP UTAH LINE 1

Discussion of the data acquisition and original processing for COCORP Utah Line 1 (Fig. 2) can be found in Allmendinger et al. (1983). For the present study, just those aspects of the data processing relevant to the SDR are mentioned. Only the eastern half (approximately) of the profile was analyzed intensively since this is the controversial region for the Sevier Desert detachment (SDD) interpretation and the area for which a significant change in the stacked section resulted from the reprocessing. The reprocessing began with the vibroseis-correlated shot records, after which three-dimensional (3D) geometry was assigned to the traces. Frequency bandpass filters were tested, but deemed destructive due to the limited bandwidth of the vibroseis source (8–31.25 Hz, with a field anti-alias filter). Starting at about CDP 2950 (Fig. 1), the profile begins to bend to the southeast, which causes the SDR to be depicted partly as a strike section.

Lateral velocity variations are expected within the central Sevier Desert basin due to the thickening of Tertiary sedimentary strata directly above the SDR and to the presence of Eocene basaltic rocks as shown, for example, by Von Tish et al. (1985) from drill-hole data (volcanic rocks crop out as close as less than a kilometer from the CDP profile [Fig. 1]). The combination of relatively low-velocity Tertiary sedimentary strata and high-velocity volcanic rocks makes for a complicated velocity structure above the SDR that could cause interruptions of the reflection (velocity push-down or pull-up). Thus the most important processing step was to derive source- and receiver-domain static corrections based on the depth to a long-wavelength rigid subsurface boundary. This is similar to the classic refraction statics approach; except that deeper and longer-wavelength lateral velocity variations are targeted rather than the usual shallow “weathered zone” velocity variations. In this way, long-wavelength velocity distortions originating in the crust above the SDR are suppressed when the seismic data are stacked in the CDP domain. Because the source-to-first receiver offset is ~400 m, it is probably not possible to resolve very shallow lateral velocity variations. But long-wavelength effects can be potentially modeled and removed. Possible problems with this approach include interpreting first arrivals accurately on the shot records and distortion of reflection hyperbolae due to large static shifts, which limits the effectiveness of CDP stacking. The resulting stacked section also has the disadvantage of introducing distortions into the travel-time section above the SDR, i.e., within the interval in which the distortions originate, and possibly smoothing over some shallow offsets.

The static correction procedure consisted of automatic first-break picking of direct- and head-wave arrivals, which were then corrected manually for every record. In many instances, a direct arrival cannot be observed, in which case a minimum value of 1500 m/s was used. A velocity model was derived in which the upper-layer velocity varied laterally, the depth to the first refactor varied, and the velocity of the second, head-wave-producing layer (infinite half-space) also varied laterally (Fig. 3). Varying the velocity of the half-space (from the head wave) was a critical step in order to account for the significant lateral variation in the rigid bedrock geology (Fig. 3). A surface-consistent residual static correction was also applied to account for very short-wavelength velocity variations, but which did not impose significant changes on the final image. Upper-layer velocities for the portion of the COCORP profile shown in Figure 4 averaged ~2400 m/s, whereas velocities from beneath the refractor averaged ~5200 m/s (Fig. 3). Planke and Smith (1991) reported average velocities for Cenozoic formations from well logs in the Sevier Desert basin ranging from 2 km/s near the surface to ~4.5 km/s at ~2 km depth below ground level. Paleozoic and Precambrian rocks were reported with average velocities ranging from 5 km/s near the surface to ~5.5 km/s at 2 km depth and increasing to over 6 km/s deeper. The velocities derived from first-break analysis are more or less consistent with these well logs observations. One consequence of applying a refraction static solution in this manner is to effectively “replace” the upper part of the earth in the stacked section (Fig. 4) with material having a velocity equal to that of
the replacement velocity (Fig. 3). This has the effect of shifting upward (in travelt ime) shallow reflections as if they were reflecting within a medium with the replacement velocity function. These effects are more pronounced where the difference between the replacement velocity and the upper layer velocity is relatively high (e.g., CDPs 2400–2800, between traveltimes 200 and 700 ms [Fig. 4A]). The refracting interface used in the static correction (Fig. 3) is shown plotted on the travel-time CDP-stacked section (Fig. 4C), which shows a good correlation between the onset of reflectivity (Fig. 4C) and the head-wave-generating surface for most of the section. A previous study applied an analogous to our approach (Branch, 1985; Smithson and Johnson, 1989) for a portion of the COCORP profile. We attempted to derive a velocity model based on tomographic ray tracing (see McBride et al. [2010] for an example of applying this technique) in order to correct for the effect of the Sevier Desert basin on the SDR image. The resulting stacked section was not appreciably different from the original version. We believe this is because steep velocity gradients in the model restricted ray penetration depth for the source-receiver offsets involved, thereby limiting the ability of the tomographic technique to resolve the critical long-wavelength statics problem in these data.

The velocity model (Fig. 3) was used to compute source and receiver domain statics prior to normal move-out (NMO) correction and CDP stacking. Muting first breaks was performed using an automatic CDP stretch mute (portions of traces stretched more than 50% were zeroed). NMO velocity analysis provided a stacking velocity function; however, due to the scarcity of coherent reflected arrivals and the general complexity of the crust, a reliable interval velocity function is difficult to obtain. We applied an apparent velocity filter (“tau-p” [vertical travel-time-slowness] filter) in the shot domain and a 5-trace mix in the stack domain (Fig. 4A) in order to reduce noise. These processes are intended to reduce the effect of noise caused by scattering, but may smooth over small structural details. The reader is directed to McBride et al. (2005) for a discussion of this filter applied to another COCORP data set. Amplitude balancing with a 1 s window automatic gain control was applied before and after CDP stacking. In order to reduce noise further, the stacked section is also shown with a post-stack coherency filter (Fig. 4B) as developed by LITHOPROBE at the University of Calgary (e.g., van der Velden and Cook, 2005). This version of the stack is post-stack processed to strongly emphasize apparent breaks in continuity of the SDR. The most notable breaks appear beneath CDPs 2400–2500 and beneath CDPs 1990–2000. Migration trials on the stacked data did little to alter the main geometrical relationships, due to the low dip of the reflector (≤11°) (see also Fig. 2).

In order to attempt a view of the SDR in a depth section, we devised a simple, vertically and laterally varying average velocity function using the variable replacement velocity applied at 0 travelt ime and increasing downward to 6 km/s at ~10 s, where sporadic reflections from the Moho discontinuity arrive (not shown herein; see Allmendinger et al. [1983]). As an independent check on this result, we then computed a depth conversion based on a smoothed version of the rms (root mean square) velocity function used to stack the data. The results of the depth conversions are shown in Figure 4B, which indicate a moderate degree of consistency between the two methods. Although such a simple approach is limited by a lack of detail, it is consistent with available regional seismic refraction data. Chulick and Mooney (2002) show an average crustal velocity for the study area of between 5.8 and 6.0 km/s, consistent with our simplified function. As a simple first-order check on the applicability of our velocity conversion, the average velocity function results in the Moho reflection arrival times on Utah Line 1 being converted to ~30 km depth, which agrees well with compilations based on modeling seismic refraction profiles (Braile et al., 1989; Chulick and Mooney, 2002) (this exercise only indicates consistency of our depth conversion with previous results, not a proof). Results from an expanding spread experiment along COCORP Utah Line 5 (Liu et al., 1986), which intersects Utah Line 1
Figure 4 (continued on following page). (A) As in Figure 2, but reprocessed as described in the text. See Figure 1 for location of the profile. Note that all seismic sections in this paper have an individual trace scaling applied. The original processing (Fig. 2) used a replacement velocity of 4500 m/s for the elevation static correction. For the reprocessed versions the replacement velocity was varied (Fig. 3). West of CDP 2209, the source static correction has been smoothed (as in Fig. 6). (B) As in Figure 4A, but with a post-stack coherency filter, as described in the text, and displayed as a variable-area no wiggle section with a negative trace bias. SDR—Sevier Desert reflection. Note that none of the other reprocessed sections has had a coherency filter applied. This section has been converted from time to depth as described in the text. The red dashes show the results of independently converting the SDR to depth using a smoothed version of the stacking velocity function. The green cross marks the depth to the SDR as predicted by Liu et al. (1986) (see text for more explanation). The reader is reminded that this is a model depth only and thus is, at best, only an approximation.
near CDP 2425 (Fig. 1), provided a generalized depth model in which the SDR was reported to be 4.8 km deep below their processing datum of 1432 m above sea level. For our processing of datum of 1900 m, this translates to a subdatum depth of 5.3 km, which matches well our model-based estimate in Figure 4B. We stress that our depth conversion should not be considered robust because good velocity constraints are lacking. In particular, the depths of some shallow reflectors in the center of the profile are likely underestimated.

Allmendinger et al.'s (1983) preliminary depth conversion is similar in some respects to our solution, but also shows important differences (Fig. 2).

RESULTS OF REPROCESSING
COCORP UTAH LINE 1

Original Processing

In order to compare the reprocessing results with the version of COCORP Utah Line 1 that has been used in most crustal-scale studies of the SDR (the version usually cited in the literature), we have accessed the original coherency-filtered stacked section available from Cornell University (Nelson, 1988). This section is displayed in Figure 2 with no further processing. The originally processed version shows the SDR as an irregular and discontinuous surface. Anders and Christie-Blick (1994) and Christie-Blick et al. (2007a) refer to offsets and misalignments of the SDR as detracting from a detachment interpretation. Significant apparent structural complexity (Fig. 2) can be seen, for example, along the shallow portion of the SDR between CDP 3000 and the eastern end of the profile; beneath the northward projection of the Clear Lake fault (CDP 2510); and expressed as apparent structural highs and lows (e.g., CDPs 2320, 1990, and 1800). Beneath CDP 3010 and again beneath CDP 3240, the seismic image of the SDR is interrupted by sharp breaks across which the apparent dip of the reflector abruptly changes. These features are likely related to changes in the upper layer velocity model. In any case, the main interpretive focus of the paper lies mainly to the west.

Reprocessing

A principal goal of the reprocessing was to determine if a smoother and more continuous travel-time image of the SDR could be obtained using conventional processing. The reprocessing strategy and parameters were thus focused on improving upper-to-middle crustal reflectivity and not on the shallow basin reflectivity, which does not accordingly show improvement. In fact, distortion has been observed in the processing of the shallow reflectors on the original section. The reprocessed version shows a more continuous and coherent travel-time image of the SDR, which is more consistent with the structural interpretation of the SDR as a detachment surface. Significant apparent structural complexity (Fig. 2) is reduced, and the apparent dip of the reflector is more consistent with the structural interpretation of the SDR as a detachment surface. The reprocessed version shows a more continuous and coherent travel-time image of the SDR, which is more consistent with the structural interpretation of the SDR as a detachment surface. Significant apparent structural complexity (Fig. 2) is reduced, and the apparent dip of the reflector is more consistent with the structural interpretation of the SDR as a detachment surface.
introduced into parts of the shallow section due to an imperfect shallow crustal velocity model. The shallow velocity structure above the SDR (including the Sevier Desert basin) is likely to be vertically and laterally complex, especially due to volcanic units interlayered with lower-velocity sedimentary strata, which could be expected to produce sharp velocity gradients. Thus the irregular appearance of the stack above the SDR may be affected by a trade-off between layer thickness and velocity uncertainties in the model. The reprocessed version is shown in Figure 4. The corresponding velocity-depth model (Fig. 3) indicates that most significant static effects will be applied between about CDPs 2000 and 3000. Thus the apparent structural complexity of the SDR (in the area of interest, which more or less corresponds to this CDP range) likely arises from the laterally varying velocity structure above the reflector. As can be seen from comparing the original and reprocessed stacks (Figs. 2 and 4A, respectively), an improvement in the continuity and linearity of the SDR has been achieved by the new processing. Applying a migration to the uncorrected time section (V on Tish et al., 1985) tends to accentuate the apparent undulations on the time section (Fig. 2). The deeper portion of the SDR (west of CDP 2600) now follows a mostly straight west-dipping line on the traveltime section (Fig. 4C), whereas the shallower portion (east of CDP 2600) dips less steeply. The degree of contrast between the “basinal” upper-layer velocity and the lower half-space replacement velocity significantly impacts the amount of time shift (and smoothing) of the SDR as well as of the shallow bright reflection above it, as seen across the middle length of the profile. In order to understand this effect better, we produced a spectrum of results using different upper layer velocities (1000–4450 m/s) while maintaining a constant replacement velocity (4500 m/s). The spectrum (Fig. 5) demonstrates how the shape and traveltimes of the reflections depend on this velocity contrast. As the upper layer velocity approaches the replacement velocity, the SDR becomes “pushed down” and generally uneven compared to the effect of using a lower upper layer velocity (e.g., 2000 m/s), which produces a smoother result while decreasing reflection arrival times. The shallow bright reflection above the SDR is shifted “upward” in time as the upper layer velocity decreases. It is likely that the final result (Fig. 4) has shifted the shallow reflector too far upward, compared to what is interpreted from well data in the area (Planke and Smith, 1991). We also experimented with the application of different levels of smoothing the static shifts and the velocity model. Smoothing may be warranted due to poor first-break picking or to unaccounted-for complexity; however, too much smoothing may allow static shifts to remain in the stack that otherwise should have been removed. Figure 6 shows an example of the effects of smoothing versus no smoothing where a small apparent irregularity in the SDR appears with smoothing.

Altogether, the reprocessed CDP section indicates a smoother and more continuous SDR between ~0.4 and 4.5 s, along a map distance of over 50 km. For example, the image of the SDR beneath the area of the Clear Lake fault projection is simpler on the reprocessed section (discussed below). A nearly flat, ~4-km-long segment of the SDR on the original section (centered beneath CDP 2400, Fig. 2) now appears as part of a smoothly dipping reflection (centered beneath CDP 2350, Fig. 4A). A broad antiformal shape, almost 20 km long, on the SDR (between CDPs 2050 and 2450, Fig. 2) is transformed to almost a straight reflection on the new section (between CDPs 2000 and 2400). Areas of poor continuity remain on the reprocessed version especially centered on CDP 2460, which appears to correspond with the northward projection of the Clear Lake fault (Figs. 1, 4A, and 4B). Small offsets (~100 ms) of the SDR persist on the reprocessed stack (e.g., below CDPs 2330, 2580, and 2630; Fig. 4A). The complexity in reflector geometry is probably not fully accounted for by the static correction, which was aimed at longer-wavelength lateral velocity effects. As pointed out by V on Tish et al. (1985), such offsets may represent unaccounted-for velocity effects originating in the shallow crust or could also represent minor faulting.

Another significant difference observed within the shallow crust on the reprocessed section is the position of an apparent “hinge” marking the change in dip located at about CDP 2600, across which the SDR increases in slope to the west and plunges deeper into the middle crust (Fig. 4A). This hinge corresponds to a gentle bend in the line of CDPs (Fig. 1), and thus seems likely to be at least partly an effect of the acquisition geometry. Furthermore, the position of such a “hinge” depends strongly on the contrast in the upper- and lower-layer velocities (Fig. 5). A prominent hinge was also observed on the original section further to the east (Fig. 2), which corresponds to a major bend in the survey. Between this “hinge” and the eastern end of the reprocessed profile, the maximum relief on the SDR, where it is most likely to correspond to an unconformity, is ~750 ms (or 2160 m, using the very simple time-to-depth conversion [Fig. 4C]). Other than the one major slope change at the “hinge,” the SDR lacks most of the apparent structural variations on the
original version of the CDP stack. For example, beneath CDP 3000 on the original section (Fig. 2), the SDR shows a reversal in apparent dip, accompanied by a complex pattern of overlapping reflections. The reprocessed section (Fig. 4A) shows a smoother and simpler image with a shallower apparent dip, but also with a loss of amplitude below this point due possibly to stronger muting of refracted arrivals.

Although neither the reprocessing parameters nor the original acquisition parameters were optimized for resolving shallow structure, we note some features of possible neotectonic interest. The best possible vertical seismic resolution (using the Rayleigh criterion), assuming 1500 m/s and 32 Hz would be ~12 m; however, a more realistic estimate, based on 4500 m/s and a peak frequency of 14 Hz, gives ~80 m. Smithsonian and Johnson (1989) interpret a west-dipping (in the plane of the section) fault cutting a Pliocene basalt reflection (their fig. 17) beneath CDP 2580 (Fig. 4A) that appears to also cut, to a lesser degree, the SDR. Such a fault cutting shallow reflectors may also be inferred from the reprocessed section (Fig. 4A), although the SDR is not so clearly offset and may in fact be unaffected by faulting. A close-up of the possible offset of the SDR can be observed on both the smoothed and unsmoothed versions of the stacked section (Fig. 6), although the offset is expressed somewhat differently depending on the static solution. Moving east along the profile, a notable offset appears on the shallowest reflection (likely from volcanic strata) where the Clear Lake fault trend intersects the profile (CDP 2460), as remarked above. Although this fault is not mapped even close to the profile, its length and relatively straight strike make it possibly the most interesting neotectonic feature that could be expressed on the profile. On the reprocessed profile (Fig. 4A), the vertical downward projection of this offset corresponds to a zone of poor continuity along the SDR, but without a clear offset of the SDR. This is in contrast to the image on the original section (Fig. 2), which shows a strong apparent disruption and narrow synformal feature beneath the fault projection. The only mapped (Fig. 1) Quaternary faults that actually are known to cross the seismic profile are part of the Drum Mountains fault zone (Oviatt, 1989), which intersects the profile with two fault strands (Fig. 2). This part of the profile previously has been interpreted as small half-graben with a west-dipping fault (Allmendinger et al., 1983), which only can be interpreted from the original profile (Fig. 2). The west-dipping fault has been interpreted to sole into another detachment, but not to interact with the SDR (Allmendinger et al., 1983). In summary, the reprocessed section lessens the evidence for offset of the SDR by high-angle normal faults; however, the poor resolving power of the COCORP data in the shallow section points to the need for high-resolution seismic surveys (e.g., with 3 m as opposed to 100 m station spacing) in order to study geologically recent faulting in the Sevier Desert.

Reprocessing: Seismic Attributes

In order to quantify the structural and seismic property variability of the SDR on the COCORP profile, several seismic attributes (e.g., reflection strength) were tested (Figs. 7 and 8). Employing a suite of attributes will more likely produce a

![Figure 6. Example of stacking with a smoothed vs. an unsmoothed source statics solution. This section is a portion of that shown in Figure 4A. Note the somewhat smoother appearance of the SDR between CDPs 2400 and 2500 on the unsmoothed version (top) as well as the slight shingling of the SDR beneath about CDP 2580 on the smoothed version (bottom). Arrows indicate areas where small offsets of the SDR appear differently on the two versions of the stack.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/6/6/840/3339836/840.pdf)
reliable characterization (e.g., see review in Chopra and Marfurt, 2006). This is especially important for the COCORP profile, due to the limited bandwidth and also due to the likelihood of varying noise and attenuation along the profile (e.g., Fig. 7). Such variation could arise from a number of factors such as near-surface geology variation and localized areas of low CDP fold. The changing orientation of the CDP profile (top, Fig. 8) and the nonuniqueness in stacking events also introduce uncertainty in the use of attributes. In an effort to reduce some of these effects, the attributes were computed from the CDP stack after correcting for spherical divergence and anelastic attenuation (as a function of traveltime) without the usual short-window gain control. Further, the results were smoothed so as to reduce the effect of possible meaningless variation (Fig. 8). As with any use of seismic attributes, the nonuniform effects of attenuation and distortion from the overlying media cannot be fully accounted for, reducing the accuracy of the attribute.

The most useful attributes were average reflection strength (Sheriff and Geldart, 1995), slope of instantaneous frequency (Sheriff and Geldart, 1995), and reflection heterogeneity (e.g., Levander et al., 1994; Bean et al., 1999). The attributes were computed for a 150 ms window centered over the SDR interpreted directly from the reprocessed stacked section. Average reflection strength provides a measure of the variation in absolute amplitude of a reflection, and thus furnishes a qualitative indication of the seismic impedance (i.e., rock properties) contrast relative to the surrounding media. The slope of instantaneous frequency is a less common seismic attribute and may be considered to provide a qualitative indication of heterogeneity. The reflection heterogeneity attribute is based on the square root of 1 plus the vertical derivative of the amplitude squared computed in a sliding window. The reflection strength attribute was also computed for the entire stacked section without amplitude balancing (Fig. 7). Lastly, a function showing the “instantaneous slope” of the SDR was extracted in order to investigate structural variations that may be too subtle to detect by visual inspection. The “instantaneous slope” was measured on a tracing of the reflection, after time-to-depth conversion, following the peak (positive) amplitude directly from the stacked data. This function does not show apparent geologic dip in the usual sense, but rather relates to the change in the depth of the SDR between each CDP sample in order to investigate structural variations that may be too subtle to detect by visual inspection. The “instantaneous slope” of the SDR was extracted for the entire stacked section without amplitude balancing (Fig. 7). Lastly, a function showing the “instantaneous slope” of the SDR was computed for the entire stacked section without amplitude balancing (Fig. 7).

Figure 7. Portion of the COCORP Utah Line 1 profile (same portion as shown in Fig. 4) processed as the reflection strength seismic attribute without gain balancing or spherical divergence or attenuation corrections and with no filters except for a pre-stack “tau-p” filter and a post-stack trace mix, as discussed in the text. In order to represent reflection strength more robustly, the attribute was computed pre-stack. Note that this attribute is not the same as that shown in Figure 8B. The color scale is arbitrary with hot colors representing high values and cold representing low. SDR—Sevier Desert reflection. Green dashed line is as in Figure 4C. Individual trace scaling has been applied to the display (each trace has had the trace amplitude divided by the mean absolute value of the trace). Note the lateral changes in noise character as expressed by mottled colored zones replacing black above and below the SDR (e.g., CDPs 1900–2060 and 2910–3200, respectively). The increased noise in these zones may frustrate the interpretation of seismic attribute patterns (Fig. 8).
section. Figure 4C shows this attribute, but with
amplitude balancing applied so as to indicate the
envelope of high strength relative to other arriv-
as in a 1000 ms automatic gain control win-
dow. Further, the computation of the reflection
strength attribute in the prestack domain with-
out amplitude balancing or frequency filtering
(Fig. 7) demonstrates the striking continuity of
the SDR over much of its length as well as its
highly discrete expression (relative to an other-
wise diffuse crustal reflectivity) between about
CDPs 2600 and 1990.

In order to integrate the results of the attribute
analysis and the reprocessed seismic data, the
CDP stacked section is redisplayed with the SDR
flattened and registered with the attribute suite
(Fig. 8B). Four regions of reflection character
may now be recognized (Fig. 8). To begin with,
from the eastern end of the profile to about CDP
2600, the “instantaneous slope” changes from
high positive values (apparent east-dipping)
of degrees (~9° from the smoothed curve)
to negative values (apparent west-dipping)
(Fig. 8A). At about CDP 2600, a second area

Figure 8 (continued on following page). Several attributes derived from the eastern portion (match-
ing the portion shown in Fig. 4) of the reprocessed COCORP Utah Line 1 (arrows on the CDP scale
show bends in the profile). All attributes are derived from a surface interpreted through the center
of the SDR on the reprocessed stacked section. This surface was first picked automatically following
the peak (positive) amplitude (i.e., the picked surface was “snapped” to the peak), after which the
surface was occasionally manually shifted to correct for cycle skipping away from the interpreted
SDR. Numbers 1–4 refer to interpreted segmentation in the SDR, based on these attributes. The
top of the diagram shows the north-south excursion of the UTM (NAD 1927) station coordinates in
order to track bends in the profile that might impart an effect on the attributes. The CDP fold and
elevation variations are also shown. (A) Computation of “instantaneous slope” (i.e., the change in
depth to the SDR between CDP traces, divided by the average CDP interval, converted to an angle
using the average velocity function applied in the time-to-depth conversion in Fig. 4B). Note that
this represents an unmigrated, apparent dip. Positive values indicate a dip to the east; negative
values indicate a dip to the west. (B) Portion of the stacked section (matching the length of profile in
Fig. 4) with the SDR shown flattened to an arbitrary traveltine in order to depict lateral changes in
reflectivity and to indicate the quality of picking the surface.
can be defined where the slope settles to a minimum value of $-25^\circ$ to $-20^\circ$ and then maintains an average value of roughly $-10^\circ$, but with a high variability until about CDP 2210. The expression of these easternmost two regions (“1” and “2”) approximately matches a pattern on the average reflection strength attribute (Fig. 8C). Average reflection strength abruptly increases from the east beginning around CDP 2650 and then generally describes a region (“2”) of unevenly high strength until about CDP 2210. The SDR for regions “1” and “2” has relatively little expression on the slope of instantaneous frequency or reflection heterogeneity (Figs. 8D and 8E, respectively), although a subtle increase in values can be observed at the 1–2 boundary, especially for the latter attribute. A third region of reflection character (“3”) can next be defined between CDPs 2210 and 1990 where the “instantaneous slope” averages roughly $-15^\circ$, is less variable, and is situated between two peaks (Fig. 8A). This region (“3”) corresponds to declining average reflection strength values (Fig. 8C). On the other hand, the slope of instantaneous frequency and reflection heterogeneity begin to show some distinct variability (Figs. 8D and 8E, respectively). The westernmost region (“4”) displays a distinct reflection character descending to smaller absolute values of dip, finally leveling off to near zero (Fig. 8A), while average reflection strength changes to a zone of intermediate, but variable, values. Both the slope of instantaneous frequency and reflection heterogeneity attributes (Figs. 8D and 8E, respectively) for region “4” now indicate the maximum variability relative to the other regions. The flattened SDR section (Fig. 8B) also suggests higher heterogeneity for the western part of region “4.” In summary, the three seismic attributes and the “instantaneous slope” can be interpreted to suggest four regions of reflection character, albeit in different ways and not always marked by sharp boundaries. Perhaps not surprisingly, the boundaries between the regions sometimes correspond to bends in the CDP profile, although the correspondence is not one-to-one (i.e., eight bends are recognized, Fig. 8). The bends likely affect the slope computation in places, but do not quite so easily explain the attribute variation. A vexing problem is the area of low CDP fold just over a critical area of interest at the “1-2” boundary (top, Fig. 8).

**DISCUSSION**

**Statement on the Controversy**

A statement of the controversy, in its most elemental form, is between the reflection being a LANF or being a chance apparent alignment of the basinal unconformity and an unrelated thrust fault. As pointed out by Christie-Blick et al. (2007a), the reevaluation of the Sevier Des-
ert detachment (SDD) interpretation has now appeared to have run its course in the literature; however, most of the reevaluations have been based in part on a data processing result now over a quarter-century old. Nevertheless, the significance of the SDD interpretation is hard to overstate. Christie-Blick et al. (2007a) appropriately cite Axen (2004): “Even one compelling example of a primary LANF (low-angle normal fault) or of LANF slip is sufficient to prove that they may form and slip at low dip, respectively.” And among data sets that are invoked to confirm the existence of LANFs, at least in continental crust, the COCORP Utah Line 1 deep seismic profile is foremost. A reprocessing of the profile is timely due to renewed interest in the SDR as a potential deep drilling target (Christie-Blick et al., 2007b).

The initial observation of the westward-dipping Sevier Desert reflection (SDR) was made by McDonald (1976), who interpreted the reflection as a Mesozoic thrust fault that had been reactivated as a low-angle normal-slip detachment (see also Mitchell and McDonald, 1987), based on several industry seismic profiles. Allmendinger et al. (1983) likewise interpreted the same reflection on the COCORP Utah Line 1 deep seismic profile as a detachment that may have originated as a Mesozoic thrust fault. Many authors have suggested that the detachment is probably a splay of the Sevier-age (Cretaceous) Pavant thrust fault (McDonald, 1976; Allmendinger and Royse, 1995; Christie-Blick et al., 2007a). Von Tish et al. (1985) further interpreted the COCORP and other seismic profiles to conclude that the SDR is just as likely a new Cenozoic low-angle normal fault (i.e., not a reactivated thrust) over much of its extent. Anders et al. (2001) point out that the detachment is usually considered to have developed with a dip not much different from its current value of 11°. Plank and Smith (1991) and Coogan and DeCelles (1996) used the COCORP profile and other industry seismic profiles to add support to the detachment interpretation by noting truncations of dipping strata above the SDR as the reflector. Proponents of the detachment hypothesis point to the presence of high-angle normal faults on seismic profiles that sole into the SDR (e.g., McDonald, 1976; Allmendinger et al., 1983; Coogan and DeCelles, 1996), while opponents have suggested that the listric faulting is related to salt withdrawal features.

Alternative interpretations that seek to negate the detachment explanation point out that the only direct, geological observations of the SDR (from drill holes) indicate “an unconformity between loosely consolidated Tertiary valley fill and the underlying dense Paleozoic bedrock” (Anders et al., 2001; Hintze and Davis, 2003). Anders and Christie-Blick (1994) and Christie-Blick et al. (2007a) cite drill-hole data and geological arguments against the need for large extensional strains in the basin in order to advocate that the SDR is really two spatially and genetically distinct segments: to the east, merely an unconformity and, to the west, a fortuitously aligned deep reflection that plunges into the middle crust and can be interpreted as a thrust fault related to the Sevier Orogeny. Anders et al. (2001) have stressed the fact that the SDR, where observed from drill-hole observations, does not show deformation fabrics that might be expected for a major fault, as seen in other well-documented detachments in the area (e.g., Cave Canyon detachment). Although the validity and relevance of the drill-hole correlations have been criticized (e.g., Allmendinger and Royse, 1995; Wernicke, 1995; Coogan and DeCelles, 2007), we are unaware of any definitive evidence of a deformation zone associated with the SDR.

Relevance of the Reanalysis

From a seismic exploration perspective, the detachment hypothesis seems more likely to predict a consistent expression of the SDR, as well as predict a relatively smooth structure for the reflector itself (detachments shown as “cartoons” tend to depict a smooth feature, although, in reality, faults need not be so simple). Such an expectation of a smooth structure would be bolstered by the conclusion of some workers that the SDR is actually a relatively recent (Cenozoic) feature of the crust. On the other hand, the thrust-and-unconformity hypothesis more probably predicts heterogeneity, especially with respect to the idea that the SDR not only has a polyphase history, but is really two (at least) distinct geological features. Seen this way, the two hypotheses may be testable by relating the results of our reanalysis to the geological predictions made by each.

The originally processed COCORP Utah Line 1 (the version most cited in the literature) shows the SDR as an irregular and somewhat discontinuous surface, even though interpretive line drawings tend to depict a smooth feature. The reprocessing (Figs. 4A and 4B) demonstrates that such irregular features could be artifacts of a laterally varying velocity structure above the SDR. The smoother structure is also apparent in the gentle rolling over and flattening out of the SDR as it rises in the crust (to a traveltime less than 500 ms) and attains an apparent dip to the east where the eastern part of the seismic profile bends around to the south (Fig. 1). This contrasts with the markedly rougher apparent structure expressed on the original seismic section (Fig. 2) that showed abrupt changes in the apparent dip of the SDR (e.g., beneath CDPs 3010 and 3240). In general, the smoother and more continuous structure of the SDR could be taken to support an interpretation involving a single geological feature, such as a LANF. A simpler structure might be especially expected for a geologically young (Von Tish et al., 1985) feature that lacks a complex history as a Mesozoic thrust fault. Our reanalysis also supports the conclusion of Von Tish et al. (1985) that the SDR is not substantially offset by high-angle normal faults as shown by some authors and thus permits large displacements along the SDD.

The application of structural and seismic attributes should be a critical part of any analysis of reflection character. This is especially crucial for the thrust-and-unconformity hypothesis since it requires separate histories for the chance alignment of two separate reflectors; however, we caution that the use of attributes may be fraught with ambiguity associated with the acquisition itself, especially the changing CDP profile orientation (Fig. 8), as well as other factors such as varying attenuation. Four distinct reflector segments can be classified based on combining the results of the attributes (Fig. 8), with two segment boundaries being the most striking (between “1” and “2” and between “3” and “4”) (Fig. 4C). The former boundary is manifested both as a change in “instantaneous slope” (steadily changing east of CDP 2600–2650 and relatively uniform on average to the west) and as a prominent increase in average reflection strength to the west where the reflector shows less slope variation (Fig. 8). The slope stabilization and the increase in reflection strength to the west of CDP 2600–2650 are suggestive of an important down-dip transformation in the physical properties of the surface defining the SDR, although the bend and low CDP fold in the profile here call for caution. The hypothesis that the SDR does not represent a detachment requires that, at some particular point moving from east to west across the Sevier Desert basin, the reflector ceases to be an unconformity and becomes a Mesozoic thrust fault. If one accepts this hypothesis, then the area around CDP 2600 could function as that point. On the other hand, proponents of the detachment hypothesis may interpret this same area in a structural sense, as a zone where steep faults displacing Tertiary sediments dip down and sole into the detachment (e.g., analogous to that shown by Allmendinger et al. [1983] and Von Tish et al. [1985] [Fig. 2]). On their detailed geological cross section located north of the COCORP profile, DeCelles and Coogan (2006) show a bend in the SDD that projects approximately into that observed at our CDP 2600.

From a purely seismic attribute point of view (using the heterogeneity measures of slope of instantaneous frequency and reflection hetero-
Further, significant seismic attribute variations can be observed along the reflector. However, each of these conclusions is predicated on critical assumptions as described above.

The resulting seismic cross section shows the SDR to be a nearly continuous geological feature over much of its length. The model depth section (Fig. 4B) recreates some of the structure of the SDR in the hand-drawn depth section presented by Allmendinger et al. (1983); however, as can be seen by comparing Figures 2 and 4, this older section shows two prominent bends in the SDR at VP 1200 and VP 1490, whereas the new section shows a smoother structure for the SDR in these areas. The SDR lacks large structural offsets apparent on the originally processed section where crossed by Quaternary fault trends (some small offsets are visible). The smoother and more continuous expression of the SDR, after reprocessing, may point to a uniform origin for the reflector, as concluded by Von Tish et al. (1985), and thus supports a LANF interpretation.

We acknowledge that two domains of structural dip may be consistent with previous studies that challenge the LANF interpretation of the SDR, in which the shallow portion of the reflector is deemed to be an unconformity, while the steeper and deeper portion is thought to be an unrelated Mesozoic thrust fault. But these two domains are not inconsistent with a LANF interpretation, particularly noting the complexity of the geology and acquisition parameters. The definition of multiple domains along the SDR is supported by seismic attribute computations, which suggest distinct segments based on physical property variations. Such variations in reflection character would not be unexpected for a detachment that has experienced a complex history, including a steeper segment that is a reactivated Mesozoic thrust as put forth by Allmendinger et al. (1983). DeCelles and Coogan (2006), in their geological cross section, show several very different kinds of geological contacts across the SDR. We also demonstrate that the SDR image is highly dependent on the details of the velocity model, including the degree of smoothing; more accurate knowledge of upper crustal velocity structure would undoubtedly improve the accuracy of the SDR image as well as of the shallow section, which has been distorted due to poor velocity constraints.

More expansively, our results have implications for the Cenozoic history of crustal extension along the eastern Basin and Range and Colorado Plateau transition. We argue for the existence of large-scale LANFs in continental crust has been based, in part, on the interpretation of the SDR as a type example of such a feature, at least from the standpoint of geophysical evidence. On a local scale, the unconformity-thrust interpretation for the SDR would suggest that a large amount of crustal extension in the Sevier Desert basin is not in evidence and, on a global scale, weakens the case for LANFs in continental crust. An important question for the unconformity-thrust interpretation is where exactly would the strong reflection from the unconformity “merge” with or be replaced by a Mesozoic thrust fault in the image? The increased smoothness and continuity of the SDR on the new image and lack of an obvious lateral discontinuity separating an unconformity and a thrust may be problematic for such an interpretation. We thus conclude that the continuity of the SDR, including the lack of large offsets, is more consistent with the detachment hypothesis than with the alternative view. Nevertheless, geologists may need to explain the significant variations in the SDR in order to make a detachment hypothesis more credible. Undoubtedly the significance of the SDR will likely continue to be debated, but the results of the reprocessing will need to be incorporated into subsequent discussions of the geophysical evidence for a LANF beneath the eastern Basin and Range.

CONCLUSIONS

A complete reprocessing of the COCORP Utah Line 1 deep seismic reflection profile provides an alternative image for interpreting the SDR and the tectonics of the Sevier Desert basin. We have applied state-of-the-art data processing techniques, including refraction static corrections in the receiver and shot record domains, noise reduction, coherency filtering, and seismic attribute analysis. We have shown that a smoother and much simpler expression of the SDR can result from application of static corrections based on a horizontally and vertically varying velocity model for the shallow earth overlying the SDR. Further, significant seismic attribute variations can be observed along the reflector. However, each of these conclusions is predicated on critical assumptions as described above.


