Listric Thrust Faulting in the Laramide Front of North-Central New Mexico Guided by Precambrian Basement Structures

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New seismic reflection images and structural analyses of the Laramide front in the Sangre de Cristo Mountains of northern New Mexico indicate the importance of listric faulting and basement weaknesses in basement-involved foreland structures. At the surface, recumbent fault-propagation folds with west-tilted backlimbs indicate that the frontal Laramide structures in this region are west-dipping reverse faults that shallow with depth. Minor fault kinematics indicates a combination of fold-perpendicular shortening and regional ENE shortening. Seismic reflection images show that these listric faults extend to depths of at least 12 km. Continued westward tilts beyond the seismic coverage suggest that these faults eventually flatten into a middle crustal detachment zone underneath the center of the range. Although this geometry could seem to be consistent with neoformed Laramide thrusts that developed in response to ENE horizontal shortening, several lines of evidence suggest this geometry was at least partially guided by pre-existing basement weaknesses. Firstly, strong but diffuse reflectivity in the middle crust about 10 km below the Laramide thrusts mimics the shape of the Laramide frontal faults. These are not likely to be a Laramide blind thrust system because no Laramide deformation is seen where they would surface to the east under the Great Plains. Secondly, N- and NNE-striking folds and faults are cut by numerous discordant structures, indicating oblique slip on pre-existing faults during transpressive deformation. We suggest that the thrusting of basement rocks of the Sangre de Cristo Range over Paleozoic sedimentary rocks was guided by pre-existing basement structures of probable Precambrian age.

1. INTRODUCTION

The Laramide orogeny is commonly associated with stresses generated by the low-angle subduction of the Farallon and Kula plates under North America [Engebretson et al., 1985;
Cross, 1986; Coney, 1987; Stock and Molnar, 1988; Bird, 1998; and Humphreys et al., 2001]. This deformation in the Rocky Mountain foreland began at about 80–75 Ma and ended in the northern and southern Cordillera at about 56 Ma and 35 Ma, respectively [Dickinson et al., 1988]. Laramide contraction resulted in formation of variously oriented basement-cored arches that are bounded by narrow zones of faulting, folding, and overturning of Paleozoic and Mesozoic strata (Figure 1). Some puzzling aspects of the basement-involved thrust faults is that they strike in a wide range of directions and vary in dip from high to low angle (Figure 1).

The controls on Laramide deformation have been the subject of extensive debate [e.g., Erslev, 1993, 2001; Woodward et al., 1997; Bird, 1998; and Cather, 1999]. Surface studies indicate abundant evidence for reactivation of earlier faults [e.g., 12 examples cited by Brown, 1988] suggesting that pre-existing weaknesses play an important role in localizing Laramide structures, particularly high-angle faults. Pennsyl-

Figure 1. Simplified Laramide tectonic map of the southern Rocky Mountains showing basement exposures (gray), Laramide sedimentary basins, and the extent of the Colorado Plateau (coarse stipple).
vanian faults generated during the Ancestral Rocky Mountain orogeny were reactivated in numerous areas in the southern Rockies [e.g. Tweto, 1975; and Stone, 1986]. Marshak et al. [2000] postulated that Ancestral Rockies and Laramide faults resulted from tectonic inversion of a Precambrian normal fault system. Timmons et al. [2001] showed that NW- and N-striking normal faults in basement formed at 1.1 and 0.8 Ga respectively. However, the role played by pre-existing weaknesses at deeper structural levels has not been thoroughly investigated due to the scarcity of deep crustal data.

Direct observations of deeper Laramide fault geometries have been very limited, and the presence of mid-crustal detachments where faults may merge is debated [Erslev, 1993; Tikoff and Maxson, 2001]. The overall geometry of Laramide arches suggests the presence of detachments or a fault-propagation folding mechanism at depth [Lowell, 1983; Oldow, 1989; Erslev, 1993]. Only at one location, the Wind River thrust, Wyoming, has the deep geometry of a Laramide fault system been imaged to middle crustal depths [Smithson et al., 1978, 1979; Lynn et al., 1983; Sharry et al., 1986]. The most recent seismic interpretations of Sharry et al. [1986] show a NE-dipping fault to 22 km depth where it appears to merge with a complex set of duplexes reaching a depth of 26 km. Gravity information [Hurich and Smithson, 1982] suggesting no Moho offsets combined with the minimum 21 km of slip on the fault strongly indicates that the Wind River fault flattens at depth into a subhorizontal detachment. In addition, a listric fault geometry that flattens into a detachment can explain the minimal deformation and remarkably uniform tilt of the NE-dipping backlimb of the Wind River arch [Erslev, 1986].

This paper presents the results of one of the seismic reflection experiments of the Continental Dynamics - Rocky Mountain project (CD-ROM) carried out in north-central New Mexico. The experiment targeted the subsurface continuation of the frontal thrust faults underlying the Sangre de Cristo mountain range (Figure 2). This location provides a unique opportunity to test for the influence of pre-existing faults because Baltz and Myers [1999] documented numerous structural highs and depocenters associated with the Pennsylvanian Ancestral Rocky Mountain deformation on the flank of the Taos trough. Their mapping defines a series of back-rotated Laramide fault blocks, which suggest basement detachment at shallow levels (10–15km) using the basement block balancing approach of Erslev [1986].

2. GEOLOGIC SETTING

The eastern front of Laramide arches in the southern Rocky Mountains of Colorado and northern New Mexico is remarkably linear (Figure 1) and trends N-S on average. In Colorado, this deformation front is dominated by NNW-striking thrust faults and folds that step right to the north, forming a ragged, sawtooth pattern of uplifted units. These structural steps range in size from 50 km between the en echelon Sangre de Cristo, Wet Mountain, and Front Range arches to 10 km along the margin of the northeastern Front Range. South of the Sangre de Cristo arch, the Laramide deformation front makes a major step to the west where Laramide structures are heavily overprinted by the more recent Rio Grande deformation. The study area (Figure 2) is located where the Laramide front makes an arcuate curve towards the west just north of this major step defining the end of the Sangre de Cristo Mountains.

Recent minor fault measurements in Mesozoic strata along the eastern front of Laramide deformation (Figure 3b, and c; Erslev, 2001; Wawrzyniec et al., 2002; Erslev et al., in press) generally show ENE-WSW shortening by thrust and strike-slip faulting, indicating transpressive deformation between the Colorado Plateau and the interior of the North American craton. The amount of regional strike-slip displacement parallel to the N-S Laramide front is highly contested, with cumulative estimates ranging from minimal [Woodward et al., 1997] to more than 100 km [Cather, 1999]. The lack of strike-slip fault zones cutting the continuous Permian and Mesozoic strata which wrap around the southern end of the Sangre de Cristo arch suggests that major Laramide strike-slip faults, if they exist, must be west of the arch axis.

Baltz and Myers [1999] compiled their geologic mapping of the southeastern Sangre de Cristo Mountains (Figure 2) and the stratigraphic evidence for extensive Ancestral Rocky Mountain deformation in north-central New Mexico. Within the context of the complicated history of pre-Laramide deformation, the diverse arrays of Laramide faults and folds along the southeastern flank of the Sangre de Cristo arch (Figure 2 and 4a) are not surprising. Fold axes and faults show trinodal distributions, with major NNW-SSE modes and lesser N-S and NNE-SSW modes. The close correlation of fault and fold patterns is expected because most of the folds are fault-propagation and detachment folds whose axes trend parallel to the strike of the underlying faults. Measurements of minor fault orientations taken from the Mora area (Figure. 3a and 4b) are oblique to fault strikes farther north (Figure 3b and c), suggesting anomalous ESE-WNW shortening and compression. The fault localities, indicated by Xs in Figure 2, are, however, adjacent to NNE-trending folds and may not sample the full regional shortening direction. This is further indicated by the dominance of NW-striking left-lateral faults in the Mora minor fault data (Figure 3a). Some degree of oblique slip is required by the diverse fold axis orientations and the fact that folds and faults change orientation along strike.

Along the NNE-trending fold and fault systems in the area (Figure 2), Baltz and Myers [1999] mapped smaller SE-NW faults with left-lateral separations offsetting the traces of the
main faults and anticlines. In comparison, such offsetting faults are rare along NNW-trending fold and fault systems. Analogous cross-cutting faults were mapped along parts of the NNE-trending East Kiabab monocline in Utah, which Tin-
thrust faults and oblique slip on NNE-striking faults, which probably have both right-lateral and thrust components to their slip.

The structural geometries defined by Baltz and Myers [1999] suggest listric Laramide faulting in 3D. In the area of the seismic line, minimal changes in Paleozoic stratigraphic thickness [Baltz and Myers, 1999] and minor post-Laramide reactivation of the faults indicate that the basement unconformity, which is well defined in the area (Figure 2), provides a good datum for evaluating the Laramide deformation. Cross-sectional profiles from Baltz and Myers [1999] (Figure 5) of faults and the basement unconformity show the contractional nature of the fault-propagation fold structures. The consistent backward tilts of the basement blocks (Figure 5) indicates rotational fault-bend folding [Erslev, 1986] on listric, or concave upward, faults at depth. The fact that backlimb tilts increase from west to east in nearly every hanging wall (Figure 5) suggests that the fault curvature increases toward the surface, causing progressively more tilting of the hanging wall as the fault tip is approached.

3. SEISMIC DATA AND INTERPRETATION

One of the seismic lines acquired during the 1999 Continental Dynamics of ROcky Mountains (CD-ROM) seismic experiment was collected with the goal of investigating the geometry of the Laramide thrusts in the southern Rocky Mountain. The surface trace of the 40 km long profile (NM_2) (Figure 2) extends from the Las Vegas basin in northern New Mexico into the basement-cored arch of the Sangre de Cristo.
Mountains. It crosses nearly normal to the strike of the frontal Sapello Fault near Mora and oblique to the Quebraditas Fault that thrusts Proterozoic over Paleozoic units (Figure 2 and 6). Impassable mountains prevented the extension of the profile farther to the west.

The seismic data were recorded with 4 large mass Vibroseis sources using 1001 active recording channels on a 25 km long seismograph array. The source interval and the group interval were 100 m and 25 m, respectively. Sweep time was 20 s. Listening time was 45 s, giving a record length of 25 s. The seismic data were processed using the Promax® processing software. Noisy traces were edited out of the dataset. Several filters were applied to attenuate and remove the surface waves, and amplitude corrections were performed to improve the S/N ratio. The processing sequence included predictive deconvolution, static corrections (refraction and surface consistent residual) to a 2200m datum plane, velocity analysis and stacking. The stack section was depth migrated with a variable velocity 2-D Kirchhoff algorithm using an attenuated velocity field derived from the prestacking velocity analysis. Basement velocities vary from 4700–5800 m/s and sedimentary rocks of the Las Vegas basin were migrated with a velocity ranging from 3300–4200 m/s. The data were not depth migrated using the velocity field derived from the seismic refraction experiment [Levander et al., this volume] due to the different tectonic setting of the two profiles.

The seismic image NM_2 (Figure 6 and 7) shows features that correspond well with the structures mapped at the surface. Each geologic unit exhibits a distinctive seismic reflectivity: the Proterozoic rocks (CDP 2300–2800) exhibit a very diffuse reflectivity, the Paleozoic rocks (CDP 1250–2300) show layering, and Mesozoic sedimentary rocks of the Las Vegas Basin

Figure 4. a) Smoothed (10° window) rose diagrams of faults and folds mapped by Baltz and Myers [1999]; b) Stereonet plots of fault planes, slickenlines and ideal sigma 1 directions for minor faults measured near Mora, NM.
exhibit a well-preserved sedimentary stratification that depicts a 2 km deep, nearly undeformed basin that thins southeastward. A west-dipping reflector at depth of 2 km (A in Figure 8) marks the base of the Las Vegas Basin. Below, at a depth of about 5 km, a set of relatively bright, discontinuous reflectors (D₂ in Figure 8) is visible between CDP 1000–2000.

The two reflectors A and D₂ are cut by a west-dipping zone of reflectivity labeled (C) at about CDP 1500 and CDP 2000, respectively. This west-dipping structure (C) surfaces at CDP 1250 and corresponds with the Sapello fault, the frontal thrust of the Sangre de Cristo Mountains in this area. From the surface the reflectivity dips 30° west and flattens to a nearly horizontal orientation between 10–11 km. Two bright, west-dipping reflections (D₁) at about 5 km depth (CDP 2300–2700) appear to coincide with the sharp bend in the line where it intersects the Quebraditas fault. Careful analysis on CDP and shot gatherers ruled out the possibility of out of plane energy reflected on the fault plane and indicated that the bright reflections (D₁) represent the energy coming from an interface below the trace of the profile. The Quebraditas fault appears to correlate with weak reflections that surface at CDP 2350.

The deeper portions of the seismic profile are dominated by highly reflective sets of west-dipping reflections (B) that appear to parallel the Sapello thrust, but at 10 km deeper levels. The structures appear to be characterized by two different sets of reflections. The shallower part is composed by two sharp, high amplitude reflectors (B₁ and B₂ at 10 km and 14 km depth respectively) that converge from the eastern end of the profile to 16 km around CDP 1400. At greater depths the seismic character of the structure changes and a zone of diffuse but bright reflectivity (B) reaches the west end of the line at a depth of 23 km. Although the continuity and the character of the reflections are variable as a function of depth, we consider these zones of reflectivity to be tectonically and genetically related, as shown below. A moderately west-dipping grain is also visible in the data at this depth, and is especially noticeable between the C and B reflections, where it seems to parallel both structures. The deeper lower crust is almost featureless in the seismic profile except for few weak subhor-
horizontal reflections that are traceable at about 34–35 km depths, which is likely too shallow to be a Moho reflection based on the CD-ROM refraction data [Levander et al., this volume].

The interpretation of the upper part of the seismic line is well constrained by surface geology and borehole data in the area [Baltz and Meyers, 1999]. The basement of the Las Vegas basin (A), on the easternmost end of the profile, is imaged at about 2 km depth. This depth corresponds to the depth of the Pennsylvanian “Great Unconformity” with underlying Precambrian basement [Powell, 1876] observed in boreholes [Baltz and Myers, 1999]. The basin is almost undeformed and shallows eastward. To the west, the Mesozoic sedimentary units stop at the mapped position of the Sapello Fault (CDP 1250), where they come in tectonic contact with the Paleozoic units that core the Sangre de Cristo arch. The Sapello Fault (C) is steeply dipping at the surface but quickly flattens to apparent dips of ~30°W and further shallows to a 10° apparent dip at 10 km depth (relative to 2200m average surface elevation) in the westernmost end of the profile. In spite of its weak signal, the Quebraditas fault can also be traced to a depth of 5 km.

The two bright reflectors, visible in the hanging wall of the Sapello Fault (D₁) and the highly reflective packages (D₂) beneath the Las Vegas basin likely represent the Proterozoic supracrustal rocks that make up El Oro Mountains on the southern end of the Rincon Range (Vadito, Ortega and Hondo Group) [Read et al., 1998] and that crop out immediately northwest of the profile. This interpretation is corroborated by the observations on a N-S reflection profile, acquired just east of the Sapello frontal thrust [Magnani et al., this volume], that images the highly reflective, nearly pure quartzites of the Ortega Fm. folded by several south-dipping ductile shear zones at a depth of 5 km beneath the Great Unconformity.

The interpretation of the structure (B) and the above west-dipping reflectivity, imaged at middle crustal depth below the Sangre de Cristo uplift, the frontal thrust and the Las Vegas basin, is not constrained by any surface and subsurface observation and is, therefore, conjectural. At first glance this west-dipping grain looks like a master detachment surface to which the Sapello and other Laramide faults would sole to the west. However, the sedimentary rocks in the Las Vegas basin above the Great Unconformity appear to be entirely undeformed by this fault system, suggesting that the age of the system is greater than Pennsylvanian-Mississippian and that the west-dipping fabric in the middle crust is an inherited feature rather than a Laramide structure. It is possible that this zone was reactivated during the Laramide, as suggested below in the discussion of structural balancing, as a mechanism to raise the western part of the basement unconformity, but the strength

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**Figure 6.** Cross section showing rocks and faults cropping out along the seismic profile NM_2 (above); first 3s of the stack section (below). The sedimentary rocks of the Las Vegas Basin are clearly visible down to 1.1s depicting a broad syncline cut to the west by the Sapello Fault (CDP 1250). West-dipping bright reflectors at CDP 2400–2600 (2–2.5s) are interpreted as the Proterozoic supracrustal rocks in the hangingwall of the Sapello thrust. Seismic data are plotted with no vertical exaggeration.
of the reflector is inconsistent with the minimal Laramide slip actually forming the reflector itself. To the east this zone of reflectivity shallows to ~15 km depth and continues into the two sharp bright reflectors (B₁) and (B₂). The interpretation of these reflectors relies on the observations along the north-south tie profile [Magnani et al., this volume] that show a system of high–amplitude, subhorizontal reflectors at 10–15 km depths that match the depth and seismic character of the two reflectors (B₁) and (B₂) observed in the NM_2 profile. The bright amplitude is indicative of a large impedance contrast that, at this depth (10–15 km) can be explained by the presence of fluids or mafic material intruded in the granitic crust. Reflectors with similar characteristics, imaged in many seismic profiles worldwide, have been interpreted as crustal magmatic intrusions [e.g. Goodwin et al., 1989; Jarchow et al., 1993]. Due to their bright reflectivity, the remarkable lateral continuity along the north-south profile and the evidence of repeated magmatic activity in this area throughout the geologic history [Keller et al., 1989; Aldrich, 1986], we interpret them as mafic sills of Proterozoic or Tertiary age, therefore suggesting that the reflectors (B₁) and (B₂) on the NM_2 line are also mafic sills. The age of these mafic intrusions is more difficult to constrain but because they seem to cross cut a broad zone of inferred Paleoproterozoic reflectivity in the cross line, we interpret them to be of either Neoproterozoic (1.1 Ga) or Tertiary-Quaternary age. Also, in this line of section, they seem to parallel the broad zone of reflectivity (B), suggesting that the sills were emplaced parallel to zones of weakness in the Precambrian crust, possibly exploiting pre-existing structural weaknesses.

Figure 7. Energy plot of the depth-migrated reflection seismic section (see Figure 2 for location), with depth from 2200 m average surface elevation plotted versus horizontal distance.
4. RESTORATION OF LARAMIDE STRUCTURES

The proposed geometries of the Sapello and Quebraditas faults, as determined from surface geology [Baltz and Myers, 1999] and the seismic data, were tested by 2D restorations of the basement unconformity using the 2DMove program of Midland Valley Exploration. An east-west, composite cross-section (C-D' from Baltz and Myers, [1999]) was simplified to show minimal footwall basement folding and extended to depth by projecting the seismic reflectors interpreted as extensions of the Sapello and Quebraditas faults into the plane of the cross-section (Figure 9a). Points on the postulated fault zone reflections were projected parallel to each fault and corrected from depth relative to 2200 m (Figure 7) to depth relative to sea level (Figure 9).

Restoration of this simplified cross-section (Figure 9b) was accomplished using fault-parallel flow [Egan et al., 1997], which provides a close approximation for basement deformation on arcuate faults. Fault-propagation folding of the hanging wall near the shallow fault tip area was not restored because folding in Rocky Mountain basement-involved structures is largely limited to shallow levels in the crust and does not appear to influence the deeper levels [Erslev, 1991]. Any simple shear components parallel to the fault zone will likewise not influence the deeper geometry of the faults and the larger-scale rotational fault-bend folding of the overlying basement blocks [Erslev, 1986].

The restoration in Figure 9b shows the general viability of the listric fault geometries indicated by both the basement block tilts and the deep crustal reflections. Two weaknesses in the restoration stand out, however. First, the non-planarity of the basement unconformity on the block backlimbs, which show antiformal shapes, suggests that fault curvatures are greater closer to the surface than were interpreted in this section. Secondly, restoration of the faults does not flatten the basement unconformity overall, with the western side of the section still substantially higher than the eastern side of the section. This latter problem can be explained in two ways. The excess elevations of the basement unconformity to the west can be remedied by steepening

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Figure 8. Geologic interpretation of the seismic data. A – Great Unconformity, B' and B” – Mafic sills of Proterozoic or Cenozoic age, B – Proterozoic (?) zone of weakness, C - Sapello thrust fault, D - supracrustal Proterozoic rocks (Hondo and Vadito Group).
the faults, which when restored, drop the basement unconformity to lower levels. This interpretation is not inconsistent with the seismic interpretation because an underestimation of the seismic velocity of the basement as well as edge effects during the depth migration processing could have resulted in incorrect depths to the reflectors in Figure 7. Alternatively, the excess elevations of the basement unconformity to the west could be due to blind duplexing at depth, an option that is consistent with the geometry of the deep reflections under these faults. This option is acknowledged, but was not pursued any further because deeper structural involvement was not necessary to balance the sections.

Simplified cross-section C-D’ was further modified according to the above observations so that faults have increased curvature near the surface and steeper dips at depth (Figure 9c). This results in a better, although admittedly non-unique, restoration (Figure 9d), with a more uniform restored elevation of a more planar basement unconformity. This interpretation has the faults continuing to flatten to the west, and is consistent with the westerly tilt of the basement unconformity from the western edge of the cross-section all the way to the Pecos Valley, 14 km to the west.

5. DISCUSSION AND CONCLUSIONS

The Laramide faults and shear zones that bound the Proterozoic uplifts are notorious for their complicated deformation history and their geometry at depth is still hotly debated. The seismic line images listric Laramide basement thrusts that can be traced from surface outcrops to a depth of 10–15 km below sea level where they appear to sole into an upper-crustal zone of reflectivity. These thrusts appear to dip up to 50–55° in surface exposures, rapidly shallow to 30° dips in the shallowest part of the seismic section, and then more gradually flatten to 20–10° at the western end of the seismic profile. The interpretation of the deeper structure is more speculative. The reflectors in the middle crust at 22–24 km beneath the Rockies ramp up to 14 km beneath the eastern front of the range and extend under the Great Plains. The character of the reflectivity along the structure appears to change from being a 2 km thick zone of scattered short reflectors to two narrow and sharp reflectors. Based on our interpretation of a crossing seismic line, we interpret the brightness of the shallow features as resulting from mafic sills that intruded subsequent to the development of the detachment system.

The age and origin of the pre-existing west-dipping structure along which the sills intruded are difficult to define. We
suggest three alternative explanations. (1) It formed during the Laramide deformation and represents a Laramide master detachment fault. (2) It formed during Pennsylvanian Ancestral Rocky Mountain deformation and possibly reactivated during the Laramide deformation. (3) It formed prior to the Ancestral Rockies and Laramide events during the early-middle Proterozoic accretionary stages [Bowring and Karlstrom, 1990] and thus any Phanerozoic movement represents fault reactivation. The first two hypotheses are supported by its flat-ramp-flat geometry, parallelism to the Sapollo Fault and depth (from 10–15 km to the east to 23–25 km to the west).

Model 1 might also be compatible with the middle crustal flow model of McQuarrie and Chase [2000], which envisions a 10 km wedge of middle crust (at about this depth) flowing eastwards from the Sevier highlands to the west, under the Colorado Plateau and Rocky Mountains and causing surface uplift of the region. However intracrustal flow from the Sevier highlands should have disrupted the seismic signature of pre-existing structures and this is in disagreement with the available observations on seismic profiles. Moreover, the absence of any Laramide uplift/anticline/dome in front of the deep structure makes the presence of a mid-crustal master detachment fault unlikely. It seems unlikely that the feather edge of the injected wedge material would have no surface expression; instead, if such features existed, they might be analogous to blind thrusts in front of thrust belts that are expressed at the surface as broad upwarps and anticlines [Fermor and Price, 1987].

The only mapped structure in the Great Plains comparable in scale to the imaged middle crustal seismic feature (B) is the Sierra Grande Uplift [Woodward, 1988]. The Sierra Grande uplift is considered Pennsylvanian in age and developed during the Ancestral Rockies deformation, although later motion may have occurred in Laramide time. Reactivation of Ancestral Rockies arches and basins during mid-Cretaceous–Eocene time has been recorded for Las Animas dome, which may represent the continuation of the Sierra Grande uplift to the north [Volk, 1972; Tweto, 1983; Merewether, 1987].

The third hypothesis, a possible Precambrian origin for the structure, provides an alternative explanation for the absence of a major uplift associated with the observed structure. The Rockies expose 1.4 Ga middle crustal rocks that were emplaced at 3–4 kbar, whereas the same age rocks in the Great Plains are rhyolitic volcanic and sedimentary materials that have never been buried to great depths. The timing of this post-1.4 Ga differential uplift is not well constrained. Some uplift, perhaps several km, took place in the Laramide as the Rockies went up relative to the Great Plains; some uplift, again perhaps several kilometers, took place in the Ancestral Rockies event, but some may also have taken place during 1.1 and 0.8 Ga extensional faulting along the Rocky Mountain front. This Precambrian faulting may have been the time of initiation of the N-S Rocky Mountain trend [Karlstrom and Humphreys, 1998]. If so, the deep reflectors may represent pre-1.4 Ga faults responsible for this uplift, consistent with the Proterozoic inheritance for mid-continent arches of Ancestral Rockies age suggested by Marshak et al. [2001].

We speculate that the deep crustal structures observed on our line probably represent shear zones/basement faults that formed during the Proterozoic and were reactivated in Ancestral Rocky Mountains and/or Laramide deformation. They appear to have been exploited as a minimum strength surface by mafic sills during the Precambrian and/or the Tertiary. By analogy to the north-south tie profile [Magnani et al., this volume], mafic bodies could have been emplaced during the magmatism that accompanied the rifting event at 1.1 Ga [Karlstrom and Humphreys, 1998] or during the Tertiary magmatic activity associated with the Jemez Lineament in New Mexico and Arizona [Aldrich, 1986; Gardner and Goff, 1984; Perry et al., 1987].

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