Oligocene Laramide deformation in southern New Mexico and its implications for Farallon plate geodynamics

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ABSTRACT

The Silver City Range in southwest New Mexico contains Proterozoic basement rocks that are overlain by a sequence of Paleozoic, Mesozoic, and Paleogene strata. These rocks are folded in a broad, NW-SE–trending, east-facing monocline that lies structurally above an east-directed thrust fault. The youngest rocks folded in the Silver City monocline are similar to other late Eocene and early Oligocene volcanic rocks of the Mogollon-Datil volcanic field; an ash-flow tuff near the bottom of the volcanic sequence gives an \(^{40}\)Ar/\(^{39}\)Ar age on sanidine of 34.9 ± 0.4 Ma (2σ), and another tuff near the top of the section contains zircons that yield a weighted \(^{207}\)Pb/\(^{206}\)U age of 34.6 ± 0.6 Ma (2σ). We interpret similar structures in the Little Burro Mountains, Lone Mountain, and Bayard area, immediately east and west of the Silver City monocline, to all be genetically related to a system of basement-involved thrust faults. Modeling of these structures from the Mangas Valley in the southwest to the Mimbres Valley in the northeast suggests ~17% total shortening. We conclude that Laramide shortening was active in southwest New Mexico generally, and the Silver City region in particular, from the Cretaceous until the earliest phase of Mogollon-Datil volcanism beginning at ~37 Ma, during which time the earliest extension in the southern Rio Grande rift was initiated. The final stage of Laramide shortening, recorded in the Silver City monocline, took place during a full of volcanism and extension from ~31.5 to ~29.3 Ma. We explain the contemporaneity of shortening, significant ignimbrite eruptions, and crustal extension as the consequence of intermittent slab breakoff and renewed underthrusting of the downdropping Farallon plate.

INTRODUCTION

The timing and location of Cenozoic crustal shortening, magmatism, and extension in the western U.S. has long been interpreted to be due to interactions between the North American and Farallon plates (e.g., Dickinson and Snyder, 1979; Severinghaus and Atwater, 1990), which are consistent with geodynamic models (e.g., Bird, 1988). Spatial and temporal patterns of magmatism (Coney and Reynolds, 1977) have led to several competing ideas, such as slab rollback, delamination, and buckling, to explain removal of the Farallon slab beneath North America (Humphreys, 2009). When and where these processes may have occurred hinge on information on the timing of cessation of Laramide shortening and its temporal relationship with magmatism. In some work (e.g., Rupert and Clemons, 1990), Tertiary volcanic rocks are used as a horizontal reference to retrodeform the effects of Basin and Range faulting; in this view, volcanism everywhere postdates shortening. Results from our study show that this view is invalid for the region around Silver City, New Mexico, where the Basin and Range, Colorado plateau, and Mogollon-Datil volcanic field come together.

GEOLOGY

The Silver City Range, a NW-SE–trending topographic high ~30 × 15 km, is immediately west of the town of Silver City, New Mexico (Fig. 1); we have mapped this range at 1:24,000 (Plate 1; Hildebrand et al., 2010). The rocks there include Proterozoic granite and metamorphic basement overlain by ~800 m of Cambrian through Pennsylvanian sandstones and limestones (Mack, 2004a; Pope, 2004; Kues, 2004; Armstrong et al., 2004). These are, in turn, unconformably overlain by the Cretaceous Beartooth Sandstone and Colorado Shale (~200–400 m thick; Nummedal, 2004). The Cretaceous rocks are overlain with very slight angular unconformity by an Eocene sequence (up to 900 m?) of undifferentiated felsic crystal-rich ash-flow and air-fall tuffs and interbedded volcanioclastic sandstones and conglomerates. These are capped with angular unconformity by Neogene basalt and basaltic andesite lava flows and up to 300 m of semiconsolidated conglomerates, sandstones, and minor mudstones of the Gila Conglomerate (Copeland et al., 2010). Cretaceous strata lie unconformably on basement to the southwest in the Little Burro Mountains due to the removal of the Proterozoic rocks from the area centered on the Burro Mountains.

All of these rocks are exposed in an east-facing monocline with moderately dipping (10°–20°) beds in the southwest (backlimb) and steeper (45°–85°) dipping beds in the northeast (forelimb) (Plate 1). The dip of the forelimb increases from northeast to southwest along strike of the axial trace. A top-to-east thrust (southwest-dipping) fault is exposed at the base of the forelimb in the southern portion of the Silver City Range (Plate 1; Hildebrand et al., 2008; Copeland et al., 2010).

Two orientations of normal faults are present throughout the range: (1) NE-trending faults and (2) NW-trending faults (Plate 1). The NE-trending set of normal faults strike perpendicular to the trend of the monocline and dip toward the NW and SE. Individual faults can be traced for 2–3 km and have displacements ranging from a few meters to a few hundred meters. This fault set is located near the hinge of the monocline between the steeply dipping forelimb and shallowly dipping backlimb. Faults commonly merge with each other along strike and in the downdip direction. They do not extend across the Silver City Range, but instead tip out on the western side of the crest of the range. Range-parallel cross sections show that the NE-SW–trending normal faults are restricted to shallow structural depths within the monocline and are somewhat evenly spaced, between 300 and 600 m.

The NW-trending set of normal faults is located along the western flank of the Silver City Range. The longest of these faults (the westernmost fault along cross section E–E') dips steeply to the west toward the Mangas Valley, a basin interpreted to have developed as a result of Neogene extension (Mack, 2004b). This fault juxtaposes the Cretaceous Colorado Shale in its hanging wall against Proterozoic basement rocks in its footwall. The map pattern in the southern part of Treasure Mountain (near

Geosphere; October 2011; v. 7; no. 5; p. 1209–1219; doi:10.1130/GES00672.1; 8 figures; 2 tables; 1 plate.

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cross section E–E′) shows this fault has ~2.5 km of throw.

The Silver City monocline, which has been recognized for almost a century, has characteristics of classic Laramide shortening structures, including basement involvement. The monocline was subdivided by Paige (1916) into three distinct segments: the Greenwood and Silver City segments, to the NE and SW, respectively, of the ~NE-SW normal fault with the largest displacement in the center of our map area, and the Lone Mountain segment, ~10 km SE of Silver City. Paige (1916) also described a monocline in the Little Burro Mountains, ~10 km southwest of Silver City.

Cather (1990, 2004) suggested that ~36 Ma marked the transition from regional shortening to extension in central New Mexico. Price and Henry (1984) suggested a similar transition took place in the Big Bend region of Texas at ~32 Ma. The cessation of Laramide-style deformation generally gets younger from Wyoming to New Mexico (Dickinson et al., 1988), so a transition from shortening to extension in the Silver City Range after 36 but before 32 Ma would fit within this trend. However there is no particular reason to expect such a gross trend to hold at every scale, nor should a trend in Wyoming and Colorado necessarily apply in New Mexico and Texas.

As pointed out by Chapin et al. (2004b), estimating the initiation of extension could be based on disparate timing data such as the change in the composition of volcanic rocks, the first normal faulting, the age of oldest sedimentary deposits preserved in a rift, or the time of the onset of rapid subsidence of rift basins. Obtaining estimates for the time of these events is not always easy, and in central New Mexico these several estimates would span a range of 20 million years (Chapin et al., 2004b). Despite these difficulties, some estimates for the age of the earliest extension in southwestern New Mexico exist that bear on the present discussion. Mack (2004b) noted the linearity of 35.4 Ma flow-banded rhyolite domes and dikes from the Goodsight–Cedar Hills area around Hatch, ~100 km to the east of Silver City, and suggested that the magmatism was “concentrated along incipient faults or fractures.” Mack et al. (1994) interpreted the basin in which these rhyolites formed to be a half graben and not a volcanomagmatic depression (cf. Seager, 1973).

Figure 1. Study location and surrounding areas. Blue labels are mountain ranges: AH—Alamo Hueco Mountains; BH—Big Hatchet Mountains; CH—Coyote Hills; CR—Cooke’s Range; GCH—Goodsite–Cedar Hills; GM—Grandmother Mountain; LB—Little Burro Mountains; LM—Lone Mountain; OM—Organ Mountains; PM—Pyramid Mountains; SCR—Silver City Range; TH—Tres Hermanos Mountains; VM—Victorio Mountains. Red labels are basins: Mim—Mimbres Valley; Mag—Mangas Valley. White labels are cities: B—Bayard; D—Deming; H—Hatch; LC—Las Cruces; L—Lordsburg; P—Playas; SC—Silver City. Green labels show approximate location of calderas erupted from 36 to 33 Ma (after Chapin et al., 2004a): A—Animas Peak caldera (33.5 Ma); E—Emory caldera (34.9 Ma); J—Juniper caldera (33.5 Ma); M—Muir caldera (35.2 Ma); O—Organ caldera (35.8 Ma); S—Steins caldera (34.4 Ma); SM—Schoolhouse Mountain caldera (33.5 Ma); T—Tullous caldera (35.1 Ma). Red lines show approximate location of Laramide-style shortening structures (after Drewes, 1981; Seager, 2004; Copeland et al., 2010). Dashed purple lines show proposed boundaries of Seager (2004) of Laramide basins and uplifts: LHTB—Little Hat Top basin; HU—Hidalgo uplift; SRB—Skunk Ranch basin; LU—Luna uplift; KB—Klondike basin; PU—Potrillo uplift; PB—Potrillo basin. Yellow line shows location of Plate 1.
Plate 1. Geologic map and cross sections of the Silver City Range, SW New Mexico (after Copeland et al., 2010). This figure is intended to be viewed at a size of 30 × 22 in. For the full-sized PDF file of the plate, please visit http://dx.doi.org/10.1130/GES00672.S1 or the full-text article on www.gsapubs.org to view Plate 1.
be the result of tectonic subsidence, are as old as 36.2 Ma (McIntosh et al., 1991) and suggest that extension must be older still.

In the following, we present data that bear on the timing of the convergence in southwestern New Mexico.

**GEOCHRONOLOGY**

The youngest rocks folded in the Silver City monocline are a sequence of volcanic (mostly rhyolitic) and volcaniclastic rocks exposed mostly in the NW part of the map area (Plate 1 and Fig. 2). Two of these units were analyzed for geochronology at the University of Houston.

Sanidine was extracted from sample TR98, a white, welded tuff with quartz, sanidine, and minor biotite phenocrysts (collected at 32° 47.658' N, 108° 21.900' W) by standard mineral separation techniques. This material was sent to the Ford Nuclear Reactor at the University of Michigan, where it was irradiated in position L-67 for 8 h. Interfering reactions were monitored by including in the irradiation package samples of CaF2 and a high-K glass. Neutron flux was monitored using Fish Canyon Tuff (FCT) sanidine, assuming a monitor age of 27.90 Ma (Cebula et al., 1986).

We are aware of other published estimates of the age of FCT sanidine, which vary by as much as 0.5% from the value we are using; the uncertainty of our age assessment is ~1% and assuming any other published age for FCT will not have any effect on our tectonic conclusions for the Silver City Range.

Unknowns and monitors were heated using a CO2 laser to achieve fusion. Gas evolved from this step was cleaned over a GP50 getter for 5 min before introduction into the MAP 215–50 mass spectrometer in static mode. Masses 40, 39, 38, 37, and 36 were analyzed over five cycles, and t-zero intercepts were interpolated based on the obtained data. All data in Table 1 are corrected for the decay of 37Ar and 39Ar as well as the interfering reactions on Ca and K. Uncertainty in the ages in Table 1 include uncertainty in J. Other details of 40Ar/39Ar analysis can be found in Herman et al. (2010).

The weighted average of 12 total fusions of individual sanidine crystals from sample TR98 is 34.9 ± 0.4 Ma (2σ) (Fig. 3 and Table 1).

### TABLE 1. RESULTS OF 40Ar/39Ar DATING OF SINGLE SANIDINE CRYSTALS FROM SAMPLE TR98

<table>
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<tr>
<th>Run ID</th>
<th>36Ar/39Ar</th>
<th>37Ar/39Ar</th>
<th>40Ar*/39ArK</th>
<th>39Ar (moles)</th>
<th>40Ar* (%)</th>
<th>Age (Ma)</th>
<th>± (Ma)</th>
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<td>0.00916</td>
<td>17.702</td>
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<td>97.0</td>
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<td>0.00632</td>
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<td>35.62</td>
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<td>0.00394</td>
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<td>94.3</td>
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<td>98.8</td>
<td>34.48</td>
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Note: Weighted average: 34.9 ± 0.4 Ma. (36Ar/37Ar)Ca = 0.000109 ± 0.000065. (39Ar/37Ar)Ca = 0.000687 ± 0.000092. (40Ar/39Ar)K = 0.020 ± 0.003.
systematic errors, and mass spectrometry are described in Shaulis et al. (2010).

Figure 4A shows photomicrographs of the zircons after being shot with the laser; Figure 4B shows the relative probability plot for the ages obtained from this analysis. The weighted average $^{206}\text{Pb}/^{238}\text{U}$ age from 14 laser spots on five different zircons is 34.6 ± 0.6 Ma (2σ) (Fig. 4B and Table 2).

**STRUCTURAL MODELING**

In order to offer a wider view of the structure of the region, we combined the cross sections in Plate 1 with data taken from Paige (1916) and Hedlund (1978a, 1978b) from the Little Burro Mountains, Skotnicki and Ferguson (2007) from the Bayard quadrangle to the east, and Jones et al. (1967) from the Santa Rita area to the east, to compile a regional cross section showing the upper crustal structure of the region between the Mangas Valley to the SW and the Mimbres Valley to the NE (Fig. 5). Figure 5A shows the present-day geologic configuration, and Figure 5B shows the same region palinspastically restored to pre–major Basin and Range faults. Slip along normal faults was restored by translating the fault-bounding blocks parallel to the fault surfaces until hanging wall and footwall cutoffs coincided. Figure 5C shows a reconstruction of the Neogene extension allowing rotation of the fault blocks. The Little Burro block in Figure 5A was rotated 8° in order to make the contact between the Eocene and Cretaceous rocks as horizontal as possible. The western portion of the rest of the section in Figure 5A was rotated 6°. This magnitude of rotation allows for ~1 km of dip slip along the normal fault bounding the Silver City Range. The magnitude of fault-block rotation may be higher as shown by the attitudes of the Eocene Tr in the northern part of the mapped area in the Silver City Range (Plate 1). Bedding in the Tr adjacent to the W-dipping normal faults ranges from 35° to 15° to the NE. Assuming that these dips are solely due to normal fault-related, fault-block tilting results in 4.6–2.1 km of dip slip, an amount broadly consistent with separations shown on cross section E–E′. The rotations employed in constructing Figure 5C lessen the regional structural relief as well as the dip of the west limbs of the Silver City and Little Burro monoclines when compared to Figure 5B, but no block rotations will unfold the monoclines seen along the west sides of the Little Burros and Silver City Range.

Normal fault-related range tilting could have occurred after or synchronous with deposition of the Eocene strata. If such faulting occurred after the deposition of these rocks, this section would have uniform dips, contrary to observation. If such faulting occurred in the Eocene, during the deposition of the volcanic section best exposed in the NW part of the range, this could have produced a series of intraformational angular unconformities within the Eocene volcanic section. However, that would mean the dip of this section of rocks would get shallower with decreasing age (it would also require a lot of the Basin and Range structures here to be older than 34 Ma). However, as we move progressively farther to the east from the main range-front fault, we see that the dip in the Eocene rocks goes from ~10°N at the base to ~40°N in the middle and back to ~15°N at the top of the section. The variation in the attitudes of the Paleozoic rocks in the SE portion of the range (with vertical dips in some parts and dips as shallow as 15° in other parts—see in particular cross sections E–E′ and F–F′ in Plate 1) is even more difficult to reconcile with an extensional model for the Silver City monocline. We therefore reject the hypothesis that this structure was formed as a result of Neogene or slightly older extension.

We wish to bring to the readers’ attention several salient points regarding Figures 5B and 5C. First, the section is dominated by three monoclines: from SW to NE, they are the Little Burro Mountains and Silver City Range monoclines (both NE facing) and the Bayard monocline (SW facing). A broad synclinorium in the Arenas Valley separates the Bayard and Silver City monoclines. The structural relief between the Little Burro monocline and the Arenas Valley synclinorium is ~4 km in Figure 5B (no rotation).
Figure 5. Regional cross section from the Mangas Valley to the Mimbres Valley compiled from data in Plate 1 as well as cross sections reported by Paige (1916), Jones et al. (1967), and Skotnicki and Ferguson (2007). Symbols as in Plate 1 with the addition of Kab—a Cretaceous andesitic breccia (Skotnicki and Ferguson, 2007). (A) Present day; (B) restored to pre–Basin and Range conditions with translation only along Neogene normal faults; (C) pre–Basin and Range restoration using rotation and translation (see text for details).
and 3 km in Figure 5C (with rotation). Second, the thickness of the Cretaceous rocks thins significantly from the center of the section to the SW. This reflects nondeposition and erosion of the Colorado Shale in the Burro Mountains, ~50 km to the SW and a general (eastward?) deepening of the western interior seaway during the Cenomanian (Nummedal, 2004; DeCelles, 2007) but dips 15° to 40° to the NE on the SW portion of the section in Figure 5B (see cross sections A–A’ and B–B’ of Plate 1). This places significant constraints for our estimates of the timing of some of the shortening in the region. Folding in the Bayard and Arenas Valley areas must have been largely complete by ~35.2 Ma based on the age of the essentially undeformed Sugarlump Tuff (McIntosh et al., 1992). However, the folding in the Silver City Range, including the Little Burro monocline, must at least in part be younger than ~34.6 Ma (the age we here report for our deformed sample FC52 at the top of the volcanic section in the Silver City monocline).

We used the software 2D Move™ to construct a 2-D forward model for the formation of the structures shown in Figure 5C. We assumed folding occurred due to slip along blind thrust faults, and we used trishear fault-propagation fold kinematics. We chose a contractional fault-propagation folding kinematic model because a west-dipping thrust fault is exposed at the base of the east-facing limb within the Silver City monocline (Plate 1; Hildebrand et al., 2008; Copeland et al., 2010). Although the surface trace of the thrust fault terminates northward, the monocline continues, implying that if the monocline and thrust are related, the fault should be present at depth to the northwest of its surface trace. We recognize that monoclines can form by extensional fault-propagation folding, but this explanation seems inappropriate for the Silver City monocline because no normal faults have been observed in the field where conceptual models (e.g., Mitra, 1993; Schlicke, 1995; Hardy and McClay, 1999) predict them to be. For an extensional origin for the Silver City monocline, NE-dipping normal faults would be expected proximal to the steep forelimb. The only significant normal faults observed in the region are SW-dipping faults associated with the Mangas Valley between the Silver City Range and the Little Burro Mountains, far from the steepest limb of the monocline.

The geometry and location of the inferred blind thrust faults are largely dictated by the spatial extent and geometry of the forelimbs and backlimbs of the Little Burro, Silver City, and Bayard monoclines. No attempt was made to model the formation of smaller-scale folds. The results of our modeling are shown in Figure 6. Our initial state (stage 1) corresponds to time of deposition of the Colorado Shale; an angular unconformity separates the Cretaceous rocks from the Paleozoic in the Silver City area and points east. Jones et al. (1967) interpret the Colorado Shale to be chronostratigraphically equivalent to the Graneros Shale, which Eicher (1965) interpreted to be entirely Cenomanian (99.6–93.6 Ma, according to Ogg et al., 2008).

In stage 2 of our model, slip along a shallow east-directed thrust fault beneath the Little Burro Mountains results in the formation of the Little Burro monocline sometime after deposition of the Colorado Shale. This results in ~0.8 km of horizontal shortening across the section. In stage 3, slip along a deeper east-directed thrust fault to the NE of the fault that moved in stage 1 causes the first phase of folding of the rocks now exposed in the Silver City monocline. Approximately 0.5 km of shortening occurs during this stage of the model. In stage 4, slip along a NE-directed thrust fault and SW-directed thrust fault results in formation of the Bayard monocline in the NE, a slightly smaller monocline immediately to the SW, and the intervening Arenas Valley synclinorium. The timing of the formation of these thrusts and associated monoclines (sequential, simultaneous, or alternating) is not specified, nor are the temporal details in this portion of our model essential to our conclusions. Approximately 0.8 km of shortening occurs during stage 4. Stage 5 is the only part of our model for which we have precise temporal information. During this stage, no deformation takes place, but ~2 km of volcanic and volcanioclastic material is deposited between ~35 and 34 Ma. During stage 6, which we argue below occurred at perhaps 30 Ma, renewed slip along the blind thrust underlying the Silver City monocline results in 2000 feet of horizontal crustal shortening, which includes the late Eocene–early Oligocene volcanic and volcanioclastic section (Tv). This modeling produces ~17% shortening from stage 1 to stage 6 (from 15.4 km to 12.7 km).

Although our modeling shows that the gross structure of the section shown in Figure 5B can be produced by movement along a sequence of three NE-directed thrust faults in the SW and on SW-directed thrust in the NE, some differences exist between Figure 5B and stage 6 in Figure 6. We don’t think these differences are significant, primarily because our model does not include erosion or the effects of the several Late Cretaceous to Paleogene intrusions seen throughout the region (in particular in the Silver City Range and Santa Rita area, Jones et al., 1967). We interpret the 20 or so small- to medium-scale, NE-trending normal faults running across the crest of the Silver City Range (Plate 1) to be the result of flexure of the monocline into a doubly-plunging structure; this flexure is also not present in our model.

**DISCUSSION**

**Structure**

The ages reported here are similar to ages of other tuffs seen in the Bayard area to the east of the Silver City Range (e.g., Sugarlump Tuff, 35.17 ± 0.17 Ma; Kneeling Nun Tuff, 34.89 ± 0.05 Ma; McIntosh et al., 1992). It is not clear nor important to our following discussion if any of the tuffs seen in the western part of the Silver City Range are the same as these or any other well-described unit in southwestern New Mexico (additional candidates include the Datil Well Tuff, the Doña Ana Tuff, the Bluff Creek Tuff, and the tuff of Woodhaul Canyon, which all issued from calderas in SW New Mexico; Chapin et al., 2004a, 2004b; Fig. 1). The 40Ar/39Ar and U/Pb data presented here establish that rocks deformed in the Silver City monocline are as young as 34.6 ± 0.6 Ma. Other undated but younger rocks that lie stratigraphically above our sample FC52 are also folded in the Silver City monocline (Plate 1). Approximately 6 km to the west of the FC52 sample location, Fin nell (1987) mapped the Bloodgood Canyon Tuff (28.05 ± 0.04 Ma, McIntosh et al., 1992) sitting on top of a sandstone unit dipping 30° to the north.

Basin and Range faulting likely resulted in minor to moderate eastward tilting of rocks in the Silver City Range and Little Burros. However, the cross sections in Plate 1 strongly suggest that the moderate to steep NE dips of the Cambrian through Eocene strata are a result of pre–Basin and Range shortening. We rule out the possibility that the Silver City monocline formed as a result of slip along a normal fault because no east-dipping normal faults within the forelimb were recognized (Plate 1). Thus, based on the failure of the extensional model and the presence of the southwest-dipping thrust fault in a position consistent with the shortening hypothesis (Plate 1), we interpret that the Silver City monocline is a consequence of shortening.

Laramide-style deformation has long been recognized in other mountain ranges in southwestern New Mexico (e.g., Seager and Mack, 1986; Seager et al., 1986; Chapin and Nelson, 1986; Nelson and Hunter, 1986), but the youngest rocks involved in most of these structures are Cenomanian or older, and therefore do not provide significant limits on estimates of the
timing of shortening, other than “post–90 Ma,” which doesn’t exclude any of the canonical range of the Laramide orogeny (80–40 Ma). Seager (2004) concluded that “Laramide contractile deformation culminated in southern New Mexico during the Paleocene and early to middle Eocene, as determined by the ages of syn- to post-orogenic [sedimentary] deposits.” Although our modeling suggests 17% shortening in the Paleocene through Oligocene, no significant clastic sequence of this age has been identified as having been sourced by the rocks now exposed in the Silver City area. Such material may have been deposited to the north and now lie beneath the substantial deposits of the Mogollon-Datil volcanic field. Conversely, it may be that the Silver City area deformation lies at the NW edge of the Potrillo uplift of Seager (2004) and development of the basin may not have been as pronounced in the center of the uplift-basin pair in Luna and Doña Ana counties to the southeast.

Our interpretation of the geology of the Silver City area is consistent with Seager’s (2004) conclusion “that the southwestern New Mexico crust failed under Laramide stresses primarily by breaking into a series of basement-cored block uplifts and intermontane basins,” but the Potrillo basin (as shown in figure 6 of Seager, 2004) cannot be extended along strike into our
field area, given our interpretation of the structure of the Silver City area in Figure 5B. Recognition of Laramide shortening in the Silver City region not present in Seager’s (2004) analysis requires a truncation of the Potrillo basin and the merging of the Potrillo and Rio Grande uplifts (mostly beneath Oligocene and Miocene volcanic cover).

Timing

Based on the structural style and timing, our data indicate that some of the shortening in the Silver City Range is younger than ~34.6 Ma. In the following, we consider the tectonic variability in southwest and south-central New Mexico in the late Eocene and early Oligocene (Fig. 7) to put the deformation in the Silver City Range in a regional context.

The Mogollon-Datil and Boot Heel volcanic fields in New Mexico, the Trans-Pecos volcanic field in Texas, and the San Juan and Central Colorado volcanic fields in Colorado were sites of significant volcanism between 37.5 and 23.5 Ma (Chapin et al., 2004a, 2004b). Volcanic activity in these fields was more or less continuous for two ~2 m.y. lulls in magmatic activity beginning at ca. 31.5 and 26.8 Ma (Chapin et al., 2004b). For the purposes of our discussion below we are assuming that Eocene and Oligocene volcanism occurred in a neutral, or more likely, extensional stress field.

During the late Eocene and early Oligocene, Laramide-style shortening, subduction-related magmatism, and extension all played important roles in the tectonic evolution of southwestern New Mexico (Fig. 7), although it seems unlikely all at the same time. Taking the well-dated early phase of volcanism from 37.5 to 31.5 Ma (Chapin et al., 2004a, 2004b) as a starting point, and noting the interpretation of early extension in the Hatch area at 36–35 Ma, we suggest that the time of the first pulse of magmatism was accompanied by minor extension and no shortening. After this, SW New Mexico experienced a pause in volcanic activity, from ~31.5 to ~29.3 Ma. We suggest this lull in magmatism coincided with the final stage of shortening recorded in the Silver City monocline; if folding of the type shown in our model was active, it seems reasonable that this would be a time without significant extension. This then places our estimate for the latest Laramide shortening in southwestern New Mexico to be within the range of 31.5 to 29.3 Ma, entirely within the Rupelian age of the Oligocene epoch. The only aspect of the geology of Silver City Range that restricts the possible range of youngest deformation is the age of nearly flat-lying basalts above the Silver City monocline (Plate 1), which likely correlate to similar late Miocene basalts in the Mimbres valley (Faulkenberry, 1999), but consideration of regional tectonics above suggests our more restricted estimate in the middle of the Oligocene. Chapin et al. (2004b) suggested “regional extension began rather haltingly”; we conclude that the end of regional shortening was similarly halting with a hiatus of ~2 m.y. preceding the final stage of shortening beginning sometime after 31.5 Ma.

Hedlund (1978a, 1978b, 1980) has described the Tertiary volcanic section in the Little Burro Mountains and northeastern Burro Mountains as consisting of a basal andesite overlain by three significant ash-flow tuffs and associated clastic rocks. The youngest of the tuffs, the tuff of Wind Mountain, is reported to have a K-Ar sanidine age of 27.1 ± 0.9 Ma (however, this was only reported as “written communication” from other workers in Hedlund, 1978a, 1978b). Preliminary structural investigation in the Little Burros is consistent with the interpretation of Paige (1916) of a broad monocline that folds the tuff of Wind Mountain. We know of no more modern (U-Pb zircon or 40Ar/39Ar) geochronology for rocks in the Little Burros that would be more trustworthy than this essentially unpublished K-Ar date. This date, if taken at face value, in combination with the observed map pattern, suggests tilting similar to that seen in the Silver City Range (and therefore also probably related to development of a Laramide-style monocline) continued into the late Oligocene (Chattian). Thus, an additional shortening stage may have occurred in southern New Mexico. However, because of the uncertainty in the geochronology of the Little Burros, we did not extend the bar in Figure 7 corresponding to the final stage of Laramide shortening past 29.3 Ma, and left Figure 6 with only six stages.

Tectonic Implications

The intermittent switching between shortening, arc magmatism, and extension suggests a tectonic model for the interaction of the North American and Farallon plates in the southwestern Rockies and southern Basin and Range (Fig. 8) in which flat subduction of the Farallon plate causes crustal shortening (plus perhaps strike-slip deformation) until ~37–36 Ma, when the downwelling slab detached beneath the Rocky Mountains, initiating the first stage of Mogollon-Datil volcanic field ignimbrites (McIntosh et al., 1992). Closely following the initiation of regional volcanism, extension begins in the southern Rio Grande rift at ~36 Ma (Mack, 2004b; Chapin et al., 2004b). Following this initial phase of volcanism, we hypothesize continued underthrusting produced the shortening seen in the Silver City Range during the interval 31.5 to 29.3 Ma. By 28 Ma, extension dominated the structural style in southwest New Mexico and the ignimbrite flareup was in full bloom in Nevada (Dickinson, 2006), New Mexico (McIntosh et al., 1992), and the Sierra Madre Occidental (Ferrari et al., 2007) due to rollback of the Farallon plate.

Our tectonic model (Fig. 8) is consistent with the tomographic data of Schmid et al. (2002), who concluded, “part of the [Farallon] plate at depth did not move with the same convergence velocity as the plate fragments at the surface.” Sigloch et al. (2008) came to a similar conclusion, based on different tomographic data; however, we suggest a slightly different chronology than Sigloch et al. (2008) based on our data.

The recognition of Oligocene Laramide deformation in southwestern New Mexico requires modifying the standard model of slab rollback of the Farallon plate (e.g., Coney and Reynolds, 1977; Atwater, 1989; Humphreys, 1995; Lawton and McMillan, 1999) by adding more underthrusting of the subducting plate after slab breakoff but before complete rollback (Fig. 8). Alternatively, sporadic episodes of shortening and extension could be consistent with Humphreys’ (1995) model of slab buckling. However, late-stage buckling would not induce the same orientation of stresses as seen during the previous stage of normal (and flat) subduction, and the orientation of the post–34 Ma deformation in the Silver City Range is consistent with most of the Laramide structures seen throughout southwest New Mexico (Seager, 2004).

DeCelles et al. (2009) have noted a broad cyclicity in Cordilleran orogenic systems in which the end of prolonged shortening events is accompanied by high-flux magmatic events. Our data suggest that, in the local environment
of southwest New Mexico, there was as much as 8 m.y. between the beginning of the ignimbrite flareup seen in the Bootheel and Mogollon-Datil volcanic fields in the Eocene and the end of shortening associated with the Laramide orogeny in the late Oligocene.

ACKNOWLEDGMENTS

Much of the University of Houston’s field program in the Silver City area was built on a foundation of work by Max Carman and Carl Norman. Alex Woronow, Kevin Cook, Sylene Robinson, and Wayne Ericson provided logistical support in the field. Tim Lawton, Nadine McQuarrie, Jolante van Wijk, Dan Miggins, and Terry Pavlis provided helpful comments and suggestions.

REFERENCES CITED


Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.

Finnell, T.L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico—Comparison with Andean volcanism in New Mexico—Comparison with Andean volcanism in New Mexico, New Mexico Bureau of Mines Open-File Report 270403a0.
Oligocene Laramide deformation in southern New Mexico


Hildebrand, R.S., Ferguson, C.A., and Skotnicki, S., 2008, Preliminary geologic map of the Silver City quadrangle, Grant County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-file Map Series, OPGM 164, scale 1:24,000, 1 plate.


