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2000, pp. 109-116. https://doi.org/10.56577/FFC-51.109

in:

Southwest Passage: A trip through the Phanerozoic, Lawton, T. F.; McMillan, N. J.; McLemore, V. T.; [eds.], New Mexico Geological Society 51 st Annual Fall Field Conference Guidebook, 282 p. https://doi.org/10.56577/FFC-51

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STRUCTURAL GEOLOGY AND LARAMIDE TECTONICS OF THE LITTLE HATCHET MOUNTAINS, SOUTHWESTERN NEW MEXICO

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Abstract—More than 3500 m of synorogenic clastic and intermediate volcanic rocks in the northern Little Hatchet Mountains were deposited unconformably upon Lower Cretaceous rocks and deformed both syn- and post-depositionally within a complex tectonic regime during latest Cretaceous to early Tertiary time. Synorogenic rocks are divided into three formations, the Ringbone (late Campanian–Maastrichtian), Hidalgo (Maastrichtian–Paleocene), and Skunk Ranch (Paleocene–early Eocene) formations. The Ringbone and Skunk Ranch formations were deposited in alluvial-fan, fluvial, and lacustrine environments, and the Hidalgo Formation represents a coeval stratovolcano complex. Synorogenic deposits are exposed in four blocks separated by high-angle faults associated with northeast-vergent thrust faults that deformed each of the synorogenic units. Thrust faults typically dip shallowly west-southwestward, pass laterally northwestward into steeply dipping left-lateral oblique-slip faults, and are flanked on the south by a high-angle right-lateral strike-slip fault. The high-angle faults that bound thrusts represent pre-existing structures that were suitably oriented to accommodate displacement during shortening. Laramide stratigraphy and structural geology suggest a two-stage Laramide event. An early Laramide (Late Cretaceous) stage consisted of basement-cored block uplifts along pre-existing northwest-trending reverse faults in the southern Little Hatchet Mountains. The Ringbone Formation was deposited in a complementary basin to the north. This was followed by late Laramide (Paleocene–Eocene) left-lateral convergent wrenching along the same northwest-trending faults. The Skunk Ranch Formation was deposited in a wrench basin formed early in this stage of deformation. The system of northeast-vergent thrusts represents a flower structure associated with wrenching. The two Laramide stages correlate with changes in direction and convergence rates of the North American and Farallon plates between 66 and 61 Ma.

INTRODUCTION

Laramide structures and strata occur in widely scattered, local exposures throughout southwestern New Mexico and southeastern Arizona. The tectonic setting of Laramide sedimentary basins contributed to the lack of regionally extensive deposits. However, Laramide units were also buried by middle and upper Tertiary volcanic and sedimentary rocks and later segmented by Basin-and-Range normal faults, which further limited exposure (Seager and Mack, 1986). The paucity of exposures and widely varying lithologies make it difficult to interpret the Laramide deformational history and tectonic origin of Laramide strata in the region. A thick, relatively well-exposed succession of synorogenic clastic and volcanic rocks in the Little Hatchet Mountains of southwestern New Mexico (Zeller, 1970) provides one of the best records of the Laramide orogeny in the southwestern United States. Detailed geologic mapping (1:12,000) in the northern Little Hatchet Mountains (Fig. 1; Hodgson, 1991) in combination with stratigraphic studies (Basabilvazo, 1991; Wilson, 1991; Lawton et al., 1993) permit refined interpretations of the structural geology, style and timing of deformation, and regional Laramide tectonic setting.

More than 3500 m of synorogenic clastic and intermediate volcanic rocks in the Little Hatchet Mountains are divided into three formations, the Ringbone (late Campanian–Maastrichtian), Hidalgo (Maastrichtian–Paleocene), and Skunk Ranch (Paleocene–Eocene) formations. The Ringbone and Skunk Ranch formations represent predominantly clastic sedimentation, whereas the Hidalgo Formation represents a stratovolcano complex. The Laramide succession unconformably overlies the Lower Cretaceous Bisbee Group, which was deposited in a regional northwest-trending rift basin (Bilodeau, 1982). In descending order, the Bisbee Group includes the Mojado Formation (1200+ m; sandstone), the U-Bar Formation (1200 m; limestone), and the Hell-to-Finish Formation (as much as 1800 m; conglomerate, red shale and sandstone) (Zeller 1970). The lower part of the Hell-to-Finish may be of Jurassic age (Lawton and Harrigan, 1998). A brief description of the Laramide stratigraphy and distribution of deposits follows. Refer to Lawton et al. (1993) for a more complete description of the Laramide stratigraphy in the Little Hatchet Mountains.

LARAMIDE STRATIGRAPHY

Ringbone Formation

The Ringbone Formation is the lowermost Laramide unit in the Little Hatchet Mountains. It is exposed in three blocks separated by faults and attains a maximum measured thickness of 1600 m east of Playas Peak in the southern block where it overlies the Lower Cretaceous Mojado Formation with angular unconformity (Fig. 1; Zeller, 1970; Basabilvazo, 1991). The Ringbone is divided into three informal mappable members termed the lower, middle, and upper members (Basabilvazo, 1991; Hodgson, 1991).

The lower member consists of limestone cobble-to-boulder conglomerate with Paleozoic and Lower Cretaceous clasts, subordinate thin-bedded feldspathic litharenite, and minor shale (Basabilvazo, this volume). The only complete (25–125 m) section of the lower member crops out in the area north and east of Playas Peak in the southern block. The lower member north of Howells Ridge appears to fill a narrow canyon cut into the Lower Cretaceous Hell-to-Finish Formation; however, this exposure may be a folded unconformable contact (T. F. Lawton, personal commun., 2000).

The middle member consists of interbedded feldspathic-to-volcanic litharenite and black–olive-gray mudstone (Basabilvazo, this volume). Complete sections of the middle member crop out east of Playas Peak. Incomplete and relatively poorly exposed sections are present north of Howells Ridge where the base is truncated by a normal fault on the east and by the Hidalgo fault on the north. Two laterally continuous tuffs in the middle member are useful marker beds (Basabilvazo, this volume). The upper tuff can be traced for more than 5 km southward from northwest of Playas Peak to the Mojado fault. The tuffs are generally thin- to medium-bedded, white, biotite-bearing tuffs. Biotite is locally very abundant in the upper tuff (Basabilvazo, 1991). A poorly exposed succession of sandstone and shale between the Skunk Ranch and Road Forks thrusts (Fig. 2) was mapped as middle member based on the presence of feldspathic and biotite-rich beds. An olistostrome deposit in the middle member (Basabilvazo, this volume) is also a good marker bed (Fig. 1).

The upper member consists of cobble-to-boulder sedimentary-clast conglomerate interbedded with sedlitharenite sandstones in the upper part (Basabilvazo, this volume). Complete sections are present south of Playas Peak where the member attains a maximum thickness of 394 m. North of Howells Ridge, an incomplete, overturned 775-m-thick section is truncated by the Howells Ridge fault. Conglomerate clasts are predominantly Lower Cretaceous (Mojado and U-Bar formations) and subordinate Paleozoic formations. Boulders of purple andesite are present in the upper 45 m of the member west of Playas Peak and under the Hidalgo Formation on two prominent hills north of Howells Ridge. Thin purplish–green andesite flows are interbedded with conglomerate west and southwest of Playas Peak.

The age of the Ringbone is late Campanian–Maastrichtian based on

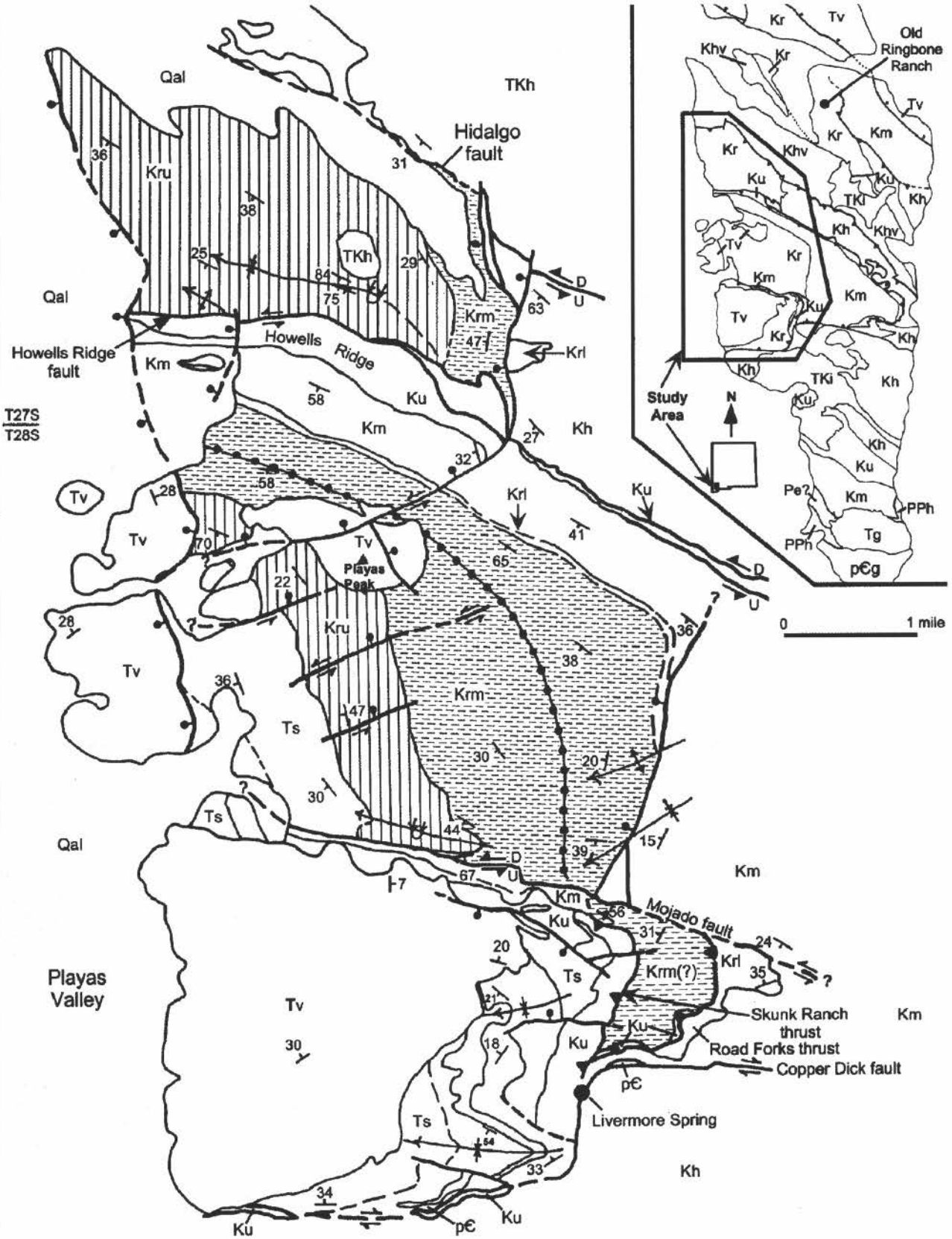


FIGURE 1. Geologic map of the northern Little Hatchet Mountains, modified from Hodgson (1991). Explanation: pCg, Precambrian granite; PPh, Horquilla Limestone; Pe? Earp(?) Formation; Kh, Hell-to-Finish Formation; Ku, U-Bar Formation; Km, Mojado Formation; Ringbone Formation divided into lower (Kru), middle (Krm), and upper (Kru) members; TKh, Hidalgo Formation; Tki Laramide intrusive rocks; Ts, Skunk Ranch Formation, undifferentiated; Tv, Tertiary volcanics; Q, Quaternary alluvium. See Figure 2 for divisions of the Skunk Ranch Formation. The line with solid circles in Krm north and east of Playas Peak is the approximate trace of an olistostrome deposit consisting of Lower Cretaceous boulders within fine-grained lacustrine deposits. See Figure 2 for detail of the Skunk Ranch thrust sheet. The western edge of the map is the western edge of R16W. Geology of the Little Hatchet Mountains inset map from Zeller (1970).

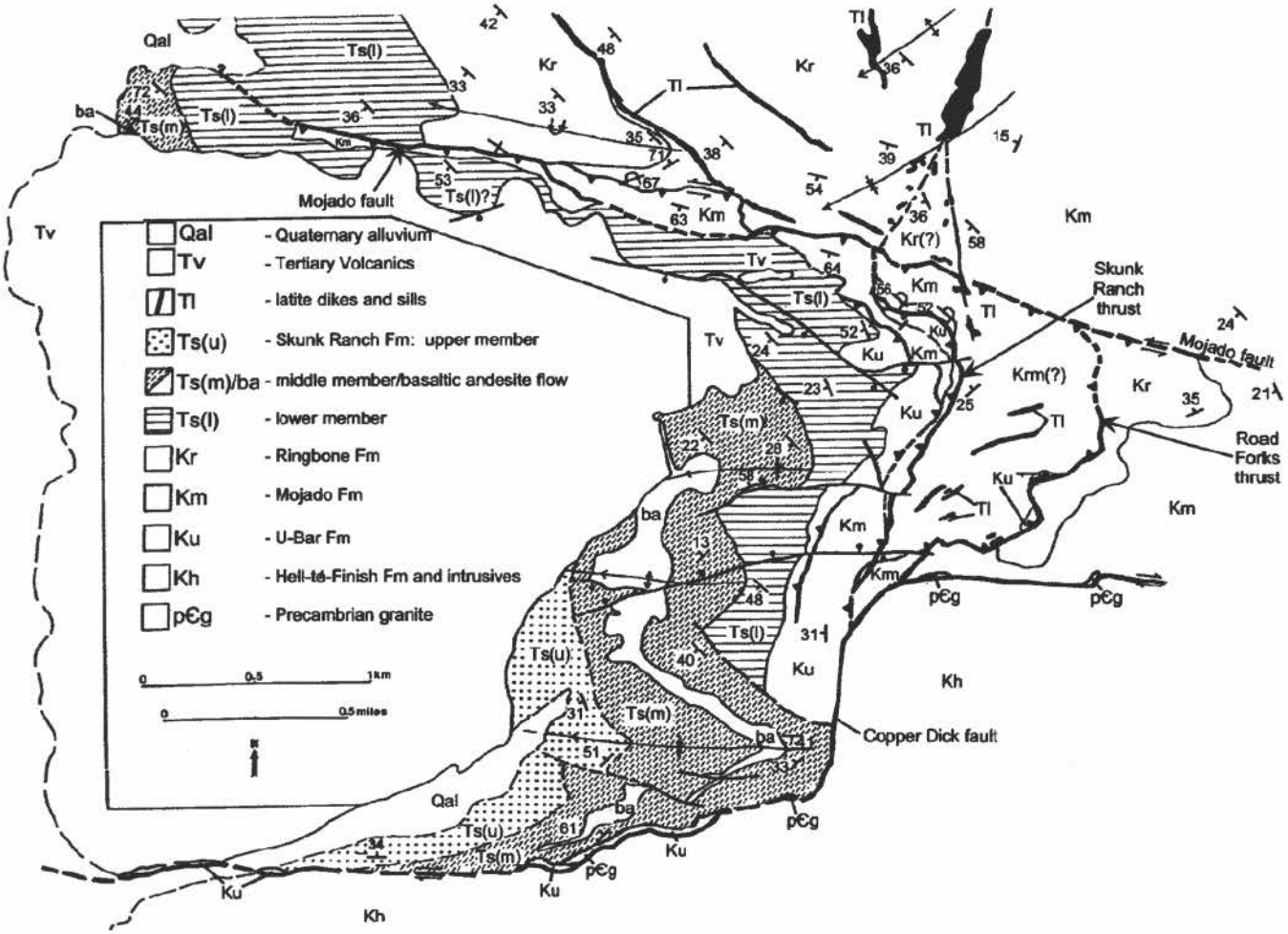


FIGURE 2. Detailed geologic map of the Skunk Ranch thrust sheet and the Copper Dick fault area, modified from Hodgson (1991). See Figure 1 for location. The Hell-to-Finish Formation south of the Copper Dick fault includes numerous Laramide intrusive rocks, mainly quartz monzonite stocks.

dinosaur bones and teeth found in the middle and upper members, pollen data (Lucas et al., 1990; Basabilvazo, 1991), and an $^{40}Ar/^{39}Ar$ date of 70.5 Ma. The $^{40}Ar/^{39}Ar$ date was obtained from a hornblende andesite flow within the upper member (Young et al., this volume).

Hidalgo Formation

The Hidalgo Formation consists of andesitic volcanic-flow breccias, basaltic and andesitic flows, and tuffs (Lucas et al., 1990; Lawton et al., 1993). The formation is exposed in a footwall syncline north of the Hidalgo fault and probably is on the order of 850 m thick (T. F. Lawton, personal commun., 1999), which is half the thickness reported by Zeller (1970). The thickness is a minimum because the upper part of the formation is cut by the Hidalgo fault (Fig. 1; Zeller, 1970; Hodgson, 1991). Hornblende-andesite flows and breccias inferred to be Hidalgo Formation cap two prominent hills north of Howells Ridge (Fig. 1). The contact with the underlying Ringbone Formation is conformable to locally unconformable, but the formation onlaps the Lower Cretaceous U-Bar Formation to the east of the study area, indicating that the contact there is an angular unconformity (Zeller, 1970; Lawton et al., 1993). Andesitic flows in the upper member of the Ringbone are similar to flows of the Hidalgo Formation, suggesting interfingering of the two formations (Hodgson, 1991). $^{40}Ar/^{39}Ar$ dates obtained from hornblende andesites near the base of the Hidalgo and from a breccia within the upper Ringbone range from 70.5 to 71.44 ± 0.19 Ma (Lawton et al., 1993; Young et al., this volume). The Maastrichtian age is compatible with stratigraphic relationships and inferred age of the upper member of the Ringbone Formation based on fossil evidence.

The Hidalgo Formation is interpreted as the margin of a stratovolcano complex located near the northern margin of the Ringbone basin. Near the old Ringbone Ranch (Fig. 1 inset), Hidalgo flows are present in the upper part of the Ringbone Formation, but the bulk of the Hidalgo overlies these beds and essentially fills much of the northern part of the Ringbone basin. Hidalgo volcanic influence is also pronounced in the upper member of the Ringbone Formation north of Howells Ridge but is much less pronounced farther south near Playas Peak, where only a few thin flows are present. Thus, clastic sedimentation continued to predominate within the Ringbone basin to the south but Hidalgo flows and volcaniclastic deposits periodically reached the southern part of the basin.

Skunk Ranch Formation

The Skunk Ranch Formation is the youngest Laramide unit exposed in the Little Hatchet Mountains. It overlies the Ringbone Formation south of Playas Peak, but overlies the U-Bar Formation south of the Mojado fault (Fig. 2). The Skunk Ranch Formation is divided into three informal mappable units termed the lower, middle, and upper members (Hodgson, 1991; Wilson, 1991). The least deformed, most continuous exposures of the lower part of the Skunk Ranch Formation are south of Playas Peak. The upper part there is cut out by a middle–late Tertiary normal fault. Exposures are more complete west of Livermore Spring and south of the Mojado fault, where all three members are present, but these exposures are complicated by numerous folds and faults. Gently dipping Tertiary volcaniclastic rocks similar to the middle Eocene Rubio Peak Formation rest with angular unconformity on the Skunk Ranch in this area and are unconformably overlain by thick ash-flow tuffs (Hodgson, 1991).

The lower member of the Skunk Ranch Formation consists of red cobble-to-boulder conglomerate and red–maroon shale and sandstone. Clasts are predominantly sedimentary rock types derived from Lower Cretaceous formations. South of the Mojado fault and west of Livermore Spring, clasts within basal conglomerates are composed almost entirely of Hell-to-Finish boulders as much as 1.5 m in diameter and subordinate dark reddish-brown, scoriaceous-to-amygdaloidal basalt clasts (Hodgson, 1991) that may have been derived from the Jurassic Broken Jug Formation of Lawton and Harrigan (1998). The lower member is approximately 110 m thick in the southern exposure but thickens to over 300 m north of the Mojado fault (Fig. 1) where the average clast size is less than in exposures south of fault.

The middle member is at least 220 m thick south of the Mojado fault where it constitutes the majority of the Skunk Ranch Formation. It consists of yellowish–gray shales, calcareous sandstone, sandy limestone, stromatolitic limestone, and massive gray limestone with crinkly laminations (Wilson, 1991). A basaltic-andesite flow breccia, similar to volcanic flows of the Hidalgo Formation, is present within the middle member (Fig. 2). The breccia is over 60 m thick west of Livermore Spring where it can be traced for 2–3 km, but thins laterally to 1–2 m to the south and to the northwest where it emerges from beneath Tertiary volcanic rocks.

Stromatolitic limestone and crinkly laminated limestone mounds overlie the breccia and interfinger with conglomerate and medium- to coarse-grained sandstone of the upper member. Limestone- and chert-cobble conglomerate of the upper member contains clasts derived mainly from Paleozoic limestones, but rare U-Bar and Mojado clasts also are present. Tertiary volcanic rocks rest with angular unconformity upon the upper member throughout the area. The maximum exposed thickness of the upper member is approximately 136 m.

The age of the Skunk Ranch is probably Paleocene–Eocene based on an ostrocode and gastropod assemblage found in the middle member (Wilson, 1991; Lawton et al., 1993). Absence of dinosaur bones and a change in paleoclimate suggested by red beds and gypsiferous shale (Wilson, 1991) in the lower member support the Paleogene age.

STRUCTURAL GEOLOGY

The east–west-trending Copper Dick fault in the central Little Hatchet Mountains divides the range into two structural domains (Fig. 1). South of the Copper Dick, thick deformed sections of Jurassic–Lower Cretaceous rocks and subordinate Paleozoic rocks are present (Zeller, 1970, Lawton and Harrigan, 1998), intruded and metamorphosed by Laramide stocks (Zeller, 1970). Laramide clastic and volcanic rocks, thrusts, and large footwall folds north of the Copper Dick fault are the focus of this study.

The structural geology of the northern Little Hatchet Mountains is characterized by the following: (1) major low-angle thrusts; (2) high-angle, oblique-slip to strike-slip faults associated with the thrusts; (3) other high-angle strike-slip faults; (4) normal faults; (5) strike-slip faults reactivated as normal faults; and (6) local thrust-related folding (Hodgson, 1991). These structures record shortening during the Laramide orogeny and are overprinted by middle–late Tertiary extensional features. The most important Laramide structural features are represented by the system of thrusts with associated high-angle oblique to strike-slip tear faults and footwall folds.

Thrusts and associated high-angle faults

The most prominent tectonic feature exposed in the northern Little Hatchet Mountains is a system of northeast-vergent thrusts and associated high-angle faults that deform each of the synorogenic formations. The thrusts typically dip west-southwest at shallow angles, roughly 15°, but grade laterally northwestward into oblique-slip faults with dips greater than 55°. The best example of this relationship is the Skunk Ranch thrust, which joins the high-angle Mojado fault (Fig. 2). All the thrusts are bounded on the south by the Copper Dick fault which accommodated strike-slip movement during emplacement of the thrust sheets. Each younger (higher) thrust was telescoped into the underlying sheet so that the final configuration is one of vertically stacked sheets. At least four allochthonous sheets are present in the northern Little Hatchet Mountains. From north to south, these are named the Hidalgo, Howells Ridge, Road Forks, and Skunk Ranch sheets, each of which overlies thrust faults of the same name (Figs. 1, 2). The Skunk Ranch thrust is the structurally highest and youngest thrust exposed in the Little Hatchet Mountains. Emplacement of the Skunk Ranch thrust sheet and oblique slip along the Mojado fault deformed the Paleocene–Eocene Skunk Ranch Formation; thus, at least the youngest thrust post-dates Skunk Ranch deposition within the study area. The major sheets (Hidalgo, Howells Ridge, and Skunk Ranch) are interpreted to lie structurally above the next oldest sheet at depth, but younger thrusts may cut older sheets at depth to the west. Each plate in the Little Hatchets was transported a minimum of several kilometers to the east-northeast (Hodgson, 1991).

Each thrust sheet has the form of an open syncline plunging gently toward the west-southwest. The syncline of the Skunk Ranch thrust sheet is probably the result of drag along the Mojado and Copper Dick faults as the thrust sheet was forced into an ever-smaller space to the east-northeast between the high-angle faults. In the eastern part of the range, the Howells Ridge thrust sheet exhibits a similar synformal morphology, termed the Howells Well syncline (Lasky, 1947).

High-angle oblique-slip faults and associated folds

Each of the thrusts passes into high-angle oblique-slip faults that form the northern boundaries of the thrust plates. Three such faults, the Hidalgo, Howells Ridge, and Mojado faults, are recognized in the Little Hatchets (Fig. 1). These faults strike from 50–80°W and dip 55–75°S, each with a generally linear trace. Structural and stratigraphic evidence suggest that the faults may have been part of a pre-existing structural grain and may have had multiple episodes of movement that included inversion of older structures, similar to structural inversions documented in the Peloncillo Mountains (Bayona and Lawton, this volume). Structurally high Lower Cretaceous rocks and composition of conglomerates in the Ringbone Formation indicate inversion, uplift, and erosion initially along the Hidalgo fault and subsequently along the Mojado fault after Ringbone deposition, but prior to deposition of the Skunk Ranch Formation.

Structural features associated with these high-angle faults indicate overall oblique-slip displacement, with the strike-slip component perhaps slightly dominant over the dip-slip component. Overturned footwall synclines are present in the Hidalgo Formation beneath the Hidalgo fault (T. F. Lawton, personal commun., 1999) and in the Ringbone beneath the Howells Ridge and Mojado faults (Fig. 1; Zeller, 1970; Rosaz, 1989; Hodgson, 1991). Overturned slices of the Mojado Formation are present beneath the imbricates of the Skunk Ranch thrust, and overturned Ringbone beds are present under the Road Forks thrust (Fig. 2; Hodgson, 1991). The footwall folds record shortening, but fold axes generally are oblique to the fault trends. The syncline beneath the Howells Ridge fault is part of a left-stepping, en echelon syncline-anticline pair that indicates left-lateral strike-slip movement (e.g., Sylvester, 1988). Furthermore, older-on-younger and younger-on-older age relationships along the Howells Ridge fault are best explained by significant lateral movement. Apparent left-lateral offset of the Ringbone Formation is also evident along the Mojado fault (Fig. 2).

Copper Dick fault

The Copper Dick fault is a major structure that crosses the central Little Hatchet Mountains and forms the southern boundary of all recognized allochthonous plates. The western part of the fault is shown on Figure 2. It continues east along the same general trend to the range boundary fault in Hachita Valley (Zeller, 1970; Lawton and Harrigan, 1998). The Copper Dick fault emplaces the Skunk Ranch and Mojado formations to the north against the Hell-to-Finish Formation and Laramide intrusions to the south.

Horses of white mylonitic U-Bar limestone are present along the west 3 km of the Copper Dick fault (Fig. 2). These horses contain a well-

developed foliation that strikes parallel to the fault and dips steeply (70–85°) to the north (Hodgson, 1991). This suggests that the fault dips steeply northward. The foliation may have formed during strike-slip motion: according to Davis (1984, p. 226), "mylonites occupy zones of profound laminar flow, especially zones of simple shear." The foliation likely developed during coeval fault movement and emplacement of intrusions to the south. Limestone-cobble conglomerates of the Hell-to-Finish Formation adjacent to the fault were also foliated and stretched as a result of fault displacement during high heat flow (Hodgson, 1991). Additionally, evidence of a strong orthogonal shortening component, such as overturned footwall synclines, is absent near the Copper Dick fault. Beds strike parallel to the east–west-trending segments of the fault, suggesting nearly pure strike-slip movement along the fault at the time of thrusting.

Small wedge-shaped horses of Precambrian granite also are present along the western segment of the Copper Dick fault (Fig. 2; Hodgson, 1991). The largest of these is associated with exposures of white quartzite, similar to the Cambrian Bliss Formation exposed at Hatchet Gap at the south end of the range, and is in fault contact with a U-Bar horse on the south and the Skunk Ranch Formation on the north. The granite was either carried along the fault by strike-slip motion or uplifted more than 1 km. Thorman and Drewes (1980) suggest that Precambrian horses present in a major fault zone in the Victorio Mountains in southwestern New Mexico indicate multiple episodes of movement on that fault. The same is probably true of the Copper Dick fault, where stratigraphic evidence indicates a complex history of fault movement. The fault was likely active during Early Cretaceous Bisbee basin extensional faulting based on thickness changes in the Hell-to-Finish and U-Bar formations across the fault (Zeller, 1970; Lawton and Harrigan, 1998). Structurally high rocks of the Hell-to-Finish and Broken Jug formations south of the fault along with the predominance of Hell-to-Finish boulders within basal Skunk Ranch conglomerates indicate uplift on the order of several kilometers along the Copper Dick fault prior to Skunk Ranch deposition.

TECTONIC SETTING

The Laramide stratigraphy and structural relationships present in the northern part of the Little Hatchet Mountains suggest two stages of Laramide deformation (Rosaz, 1989; Hodgson, 1991; Lawton et al., 1993). Interpreted in the context of structural features exposed in the southern part of the Little Hatchets and in the Big Hatchets, Animas, and Sierra Rica, a clear picture emerges of two separate Laramide tectonic phases in southwestern New Mexico. An early Laramide (Late Cretaceous) stage consisted of basement-cored block uplifts along high-angle northwest-trending reverse faults. The early stage of uplift was followed by late Laramide (Paleocene–Eocene) left-lateral convergent wrenching along the same northwest-trending fault zones (Hodgson, 1991).

Stage 1—block uplifts

The first stage of the Laramide orogeny in southwestern New Mexico and southeastern Arizona began during the Late Cretaceous (Campanian?) and was characterized by basement-cored block uplifts along northwest-trending reverse faults with associated complementary basins (Seager and Mack, 1986). Structural and stratigraphic evidence indicates that one such uplift was present near the south end of the Little Hatchet Mountains (Hidalgo uplift of Seager and Mack, 1986), where an uplift-bounding fault zone consists of a series of northwest-trending high-angle faults exposed between Granite Pass and Hatchet Gap (Fig. 3; Zeller, 1970; Seager and Mack, 1986; Hodgson, 1991). The Copper Dick, Mojado, and Hidalgo faults in the central Little Hatchet Mountains may be genetically or temporally related subsidiary faults along which uplift also occurred.

The Granite Pass fault probably is a reactivated basement structure that has a history of recurrent movement since the Precambrian or early Paleozoic, similar to many complex northwest-trending Laramide faults throughout southwestern New Mexico and southeastern Arizona (Titley, 1976; Drewes, 1981; Bilodeau, 1984). Although the Granite Pass fault could have Precambrian origins, there is no direct control on movement prior to the middle–late Paleozoic, when the fault was the approximate hingeline of the northwest-trending Pennsylvanian Pedregosa basin (Kottlowski, 1965; Zeller, 1965; Thompson, 1982). It was reactivated as a normal fault during Early Cretaceous extension and formation of the Bisbee basin, as suggested by the strong northwest trends on Lower Cretaceous isopach maps (e.g., Thompson, 1982) and the superposition of the Bisbee basin upon the Pedregosa basin.

Nearly 5000 m of upper Paleozoic through Lower Cretaceous strata are present north of the Granite Pass fault zone (Zeller, 1970; Lawton and Harrigan, 1998). Disregarding lower and middle Paleozoic rocks, the total suggested stratigraphic throw across the fault zone is almost 5 km. If multiple episodes of movement along this fault prior to Laramide movement caused thickening, thinning, or erosion of various units across the fault zone, then the total amount of Laramide displacement was probably less than the total apparent stratigraphic throw (Hodgson, 1991). Additionally, significant throw could have occurred during later convergent wrenching (Hodgson, 1991).

The Granite Pass fault zone is inferred to extend northwestward into the northern Animas Mountains (Seager and Mack, 1986; Wilson, 1986; Donnan, 1987; Hodgson, 1991) and southeastward between the Sierra Rica and Big Hatchet Mountains (Fig. 3; Seager and Mack, 1986; Hodgson, 1991). In the northern Animas Mountains, the inferred extension of the Granite Pass fault zone is a high-angle reverse fault, which is largely intruded by Tertiary quartz monzonite (Fig. 3; Wilson, 1986; Donnan, 1987; Hodgson, 1991). Upper Paleozoic strata in the southern block are uplifted and juxtaposed against Lower Cretaceous strata in the northern block (Wilson, 1986; Donnan, 1987). The stratigraphic throw is 1.2–1.8 km based on thicknesses of Paleozoic and Lower Cretaceous units reported in Zeller and Alper (1965) and Donnan (1987). Evidence that this fault is a continuation of the Granite Pass fault zone comes from oil test wells drilled in the area. North of the projected trace of the Granite Pass fault zone west of the Little Hatchet Mountains, the KCM no. 1 Cochise well encountered Lower Cretaceous Mojado Formation beneath valley fill, but south of the fault, Paleozoic rocks were encountered beneath the valley fill in the Cockrell No. 1 well (Thompson, 1982). Southeast of the Little Hatchet Mountains, the main fault strand passes south of the Tidball-Berry well because southwest-dipping Mississippian rocks crop out at the surface near the well but Precambrian granite occurs on the eastern flank of the Big Hatchet Mountains a short distance to the southwest. The well was probably drilled in a large horse of Paleozoic rocks within the fault zone.

As uplift began along the Granite Pass and subsidiary faults, detritus from Lower Cretaceous and Paleozoic rocks was deposited in a northwest-trending basin adjacent to the Hidalgo uplift (Seager, 1983; Seager and Mack, 1986; Basabilvazo, 1991; Lawton et al., 1993). The Ringbone Formation in the Little Hatchet Mountains is a northward-thinning clastic wedge that records initial Laramide deformation and evolution of the Hidalgo uplift/basin during the first tectonic phase. The age of the lower member of the Ringbone Formation indicates that initial uplift began during the Campanian (Lucas et al., 1990; Basabilvazo, 1991; Lawton et al., 1993); however, lower member conglomerate, lying unconformably on the Hell-to-Finish Formation north of Howells Ridge, indicates uplift of several thousand meters along the Hidalgo fault prior to or during deposition of the lower member (Fig. 1; Hodgson, 1991). The lower member records deposition within a southeast-flowing axial-fluvial system adjacent to dispersal systems that shed gravel northeastward from the rising Hidalgo uplift south of the Granite Pass fault zone (Lawton et al., 1993) or from uplift along the Copper Dick fault. In addition, detritus may also have been shed southward from uplift along the Hidalgo fault to the north (Basabilvazo, 1991).

Sedimentation and paleoflow directions within the middle and upper members suggest major paleogeographical changes during evolution of the uplift and basin. Paleocurrents became dominantly northeast flowing, indicating development of tranverse drainages with a relatively deep lake in the basin depocenter. The paleocurrent direction and the change in sedimentation from fine-grained feldspar-rich sediments of the middle member to sedimentary-cobble conglomerates of the upper

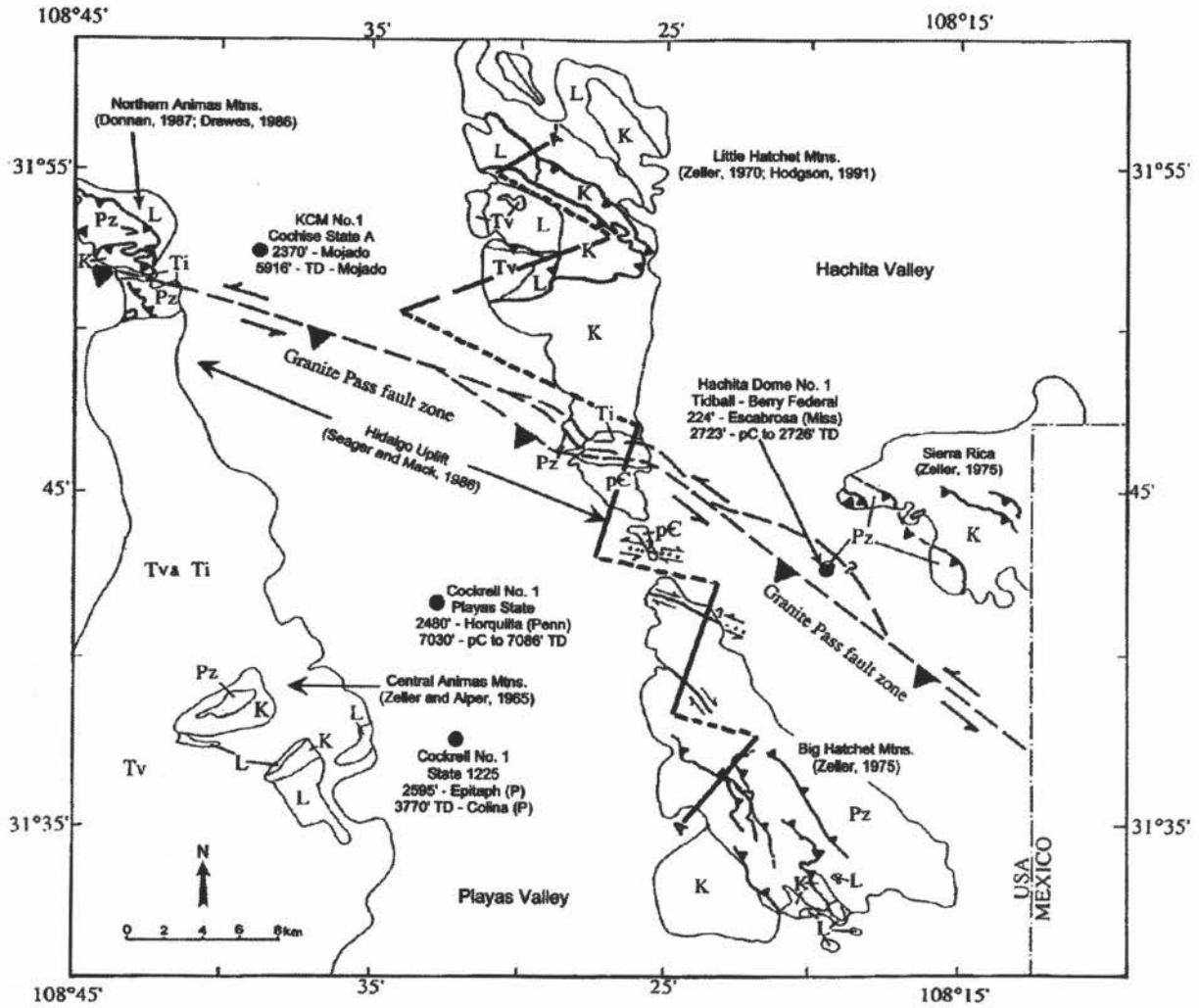


FIGURE 3. Granite Pass fault zone in southwestern New Mexico and selected Laramide deformational features. Oil wells indicate first unit encountered beneath valley fill and formation at total depth (Thompson, 1982). Line of section (A–A') of Figure 4 indicated. pЄ, Precambrian granite; Pz, Paleozoic rocks; K, Lower Cretaceous; L, Laramide clastic rocks; Ti, Tertiary intrusives; Tv, Tertiary Volcanics.

member suggest more dominant uplift along the Granite Pass fault zone that cut off volcanic sources being tapped to the west (Basabilvazo, this volume). Volcanism was coeval with clastic sedimentation during stage one as indicated by interbedded thin andesite flows and andesite clasts within conglomerate of the upper member of the Ringbone Formation.

Stage 2—wrench tectonics

The second major stage of Laramide deformation began during the Paleocene and involved convergent wrenching along the same west-northwest- to northwest-trending faults that accommodated uplift during the first stage. Left-lateral convergent wrenching produced flower structures or half-flower structures (e.g., Wilcox et al., 1973; Harding, 1985) along the fault zones that deformed rocks as young as early Tertiary. The conspicuous Laramide structures of the Little Hatchet Mountains were formed during this stage of deformation. This stage, recorded by deposition of the Skunk Ranch Formation, represents a distinct and separate style of deformation from stage one. Following a hiatus, a major change in sedimentation patterns by the time of Skunk Ranch deposition is indicated by: (1) absence of dinosaur fossils; (2) presence of Paleocene–Eocene ostrocodes and gastropods; (3) presence of gypsiferous shale and red-beds indicating hot and dry conditions compared to a more tropical or subtropical climate during Ringbone deposition; and (4) superposition of the southern Skunk Ranch depocenter upon a post-Ringbone uplift.

Major structures associated with stage-two deformation in the Little Hatchets and the surrounding mountain ranges are shown on Figure 3. Thrusts are most prominent north of the Granite Pass fault zone in the Animas, Little Hatchets, and Sierra Rica, where they are generally oriented northwest-southeast and verge northeast–east-northeast (Zeller, 1970; Zeller, 1975; Drewes, 1986; Seager and Mack, 1986; Donnan, 1987). South of the fault zone in the Big Hatchet and Animas mountains, thrusts also generally trend northwest–southeast but verge to the southwest (Zeller, 1975; Drewes, 1986; Drewes 1991). The opposing vergence of thrusts on either side of the Granite Pass fault zone produces a striking mirror-image symmetry about the fault. This suggests that structures north and south of the fault are genetically related and that the Granite Pass fault must be involved. A cross-section through the Little Hatchet Mountains, Granite Pass, and Big Hatchet Mountains (parallel to the direction of thrusting) illustrates a flower-structure relationship of the thrusts to the Granite Pass fault zone (Fig. 4). The thrusts in the Little Hatchet Mountains are inferred to steepen abruptly into the fault zone, as do thrusts in the Animas Mountains (Wilson, 1986; Donnan, 1987).

The observed symmetry across the fault zone, orientation of thrusts, and inferred steepening of thrusts into the fault are best explained by left-lateral convergent wrenching. The system of northeast-vergent thrusts in the Little Hatchet Mountains is interpreted as a half-flower structure (or a full flower with the other half concealed beneath Playas Valley) generated by this mechanism. The pre-existing faults in the northern Little Hatchets were properly oriented to accommodate thrusting generated by wrenching along the Granite Pass fault to the west-

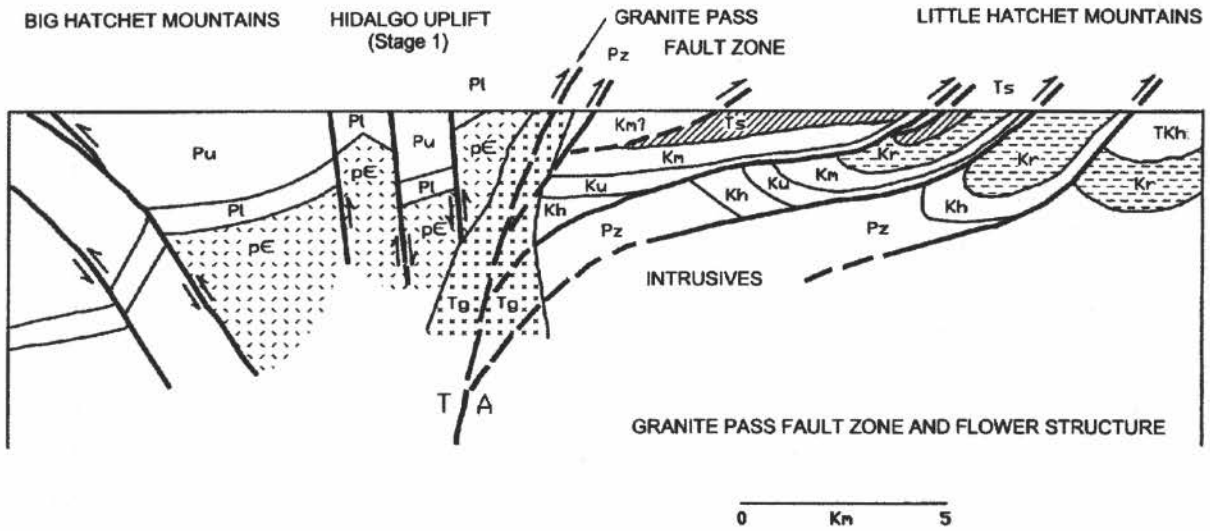


FIGURE 4. Diagrammatic cross-section through the Little Hatchet Mountains, Granite Pass fault zone, and Big Hatchet Mountains, showing the relationship of thrusts to the Granite Pass fault zone. The line of section is shown on Figure 3 (modified from Seager, 1983). Symbols as in Figure 1, with additions of Pz, undifferentiated Paleozoic strata; Pl, lower Paleozoic strata; Pu, upper Paleozoic strata; Kr undifferentiated Ringbone Formation

southwest. The thrusts in the Sierra Rica and Big Hatchet Mountains may represent a full flower structure.

Shifting basin depocenters in the northern Little Hatchet Mountains also support the wrench model. One of the most conspicuous complexities in the northern Little Hatchet Mountains is the distribution of the Skunk Ranch Formation. The presence of folded Skunk Ranch Formation above the Ringbone Formation in the footwall of the Mojado fault, but above the U-Bar in the Skunk Ranch thrust sheet indicates that emplacement of the sheet post-dates deposition of the lower member of the Skunk Ranch Formation. Deposition of the Skunk Ranch Formation on the hanging wall must have followed post-Ringbone uplift along the Mojado fault. Southward coarsening of the lower member of the Skunk Ranch suggests that basal conglomerates south of the Mojado fault filled an asymmetric basin bounded on the north by the former uplift along the Mojado fault. The basin developed as a result of normal faulting along a southward extension of the north–south oriented fault between the Ringbone and Mojado formations (Lawton et al., 1993) or along the western segment of the Copper Dick fault. The basin was filled from the east or south, eventually resulting in onlap of deposition onto the footwall of the Mojado fault. Subsidence continued in the half-graben basin locus as suggested by the thickness of the flow breccia, but subsidence became more pronounced to the north where the northern locus of the Skunk Ranch basin overprinted the former Ringbone basin.

Volcanism, which began during the Late Cretaceous, apparently continued at least until deposition of the middle member of the Skunk Ranch Formation. Thin, volcanic-rich sandstone beds in the lower member south of Playas Peak suggest some connection with Hidalgo volcanism; however, the southern Skunk Ranch depocenter was isolated from the locus of volcanic activity until deposition of the middle member of the Skunk Ranch Formation. Early Laramide uplift along the Hidalgo fault to the north may have formed a barrier to Hidalgo flows. The barrier apparently was breached during deposition of the middle member of the Skunk Ranch, permitting a major flow to reach the southern Skunk Ranch depocenter (Fig. 2; Lawton et al., 1993), possibly from the east or northeast as evidenced by northward thinning of the flow. Alternatively, the flow may have originated from a separate non-Hidalgo volcanic center, perhaps related to intrusion of late Laramide stocks south of the Copper Dick fault.

Laramide stress field and plate tectonics

The two-stage model suggested for Laramide deformation in southwestern New Mexico correlates well in timing and style of deformation with the early and late Laramide phases of Chapin and Cather (1981). They advocate a block uplift model for the early Laramide until 61 Ma (Cather, 1991) followed by late Laramide right-lateral wrenching along reactivated north- to northeast-trending basement faults and correlate the change in style of deformation with a change in the orientation of the maximum principal stress axis from east-northeast–west-southwest to northeast-southwest. In contrast, in southwestern New Mexico the style and timing of deformation is better explained by early northeast–southwest-directed stress and later east-northeast–west-southwest-directed stress. This seeming conflict might be explained by several important differences including: (1) pre-existing basement faults trend northwest to west in southwestern New Mexico, whereas pre-existing basement flaws east of the Colorado Plateau trend north to northeast, and (2) southwestern New Mexico lay between the subduction zone and Colorado Plateau; the area studied by Chapin and Cather (1981) lay to the north and east of the Colorado Plateau (Coney, 1978; Dickinson and Snyder, 1978; Dickinson, 1981).

The early Laramide greatest principal stress was approximately northeast–southwest for early Laramide intrusions and oldest late Laramide intrusions in southwestern New Mexico and adjacent parts of Arizona (Heidrick and Titley, 1982). This is nearly orthogonal to Laramide structures in southwestern New Mexico and would be conducive to the formation of block uplifts if there were high fluid pressures or weak fault-gouge minerals present in the fault zones to reduce shear strength (Sibson, 1995). Data from Lordsburg, the Little Hatchet Mountains, and Tyrone indicate that late Laramide greatest principal stress was east-northeast–west-southwest, which would produce left-lateral strike-slip motion on pre-existing northwest-trending faults (Heidrick and Titley, 1982).

The Laramide stress field ultimately resulted from the interaction of the Farallon and North American plates. The change in stress field can be explained by changes in the directions and rates of convergence of both plates during the early Paleogene (Fig. 5; Engebretson et al., 1984; Jurdy, 1984). Initially, the pre-existing structural grain in southwestern New Mexico was oriented at a high angle to the subduction trench, which resulted in a local northeast–southwest-oriented stress field and uplift along reactivated northwest-trending structures during the early Laramide. Changes in plate motion between 66 and 60 Ma caused a redistribution of stress in the North American plate resulting in left-lateral convergent wrenching along the pre-existing structures in southwestern New Mexico and southeastern Arizona.

ACKNOWLEDGMENTS

Financial support for field research was provided by the Clemons Field Scholarship, New Mexico Geological Society, and Wemlinger Scholarship Fund. Thanks to Stephanie Furgal and the Institute of

Tectonic Studies at New Mexico State University for assistance with figures. Reviews by George Basabilvazo and German Bayona improved the content and clarity of the paper.

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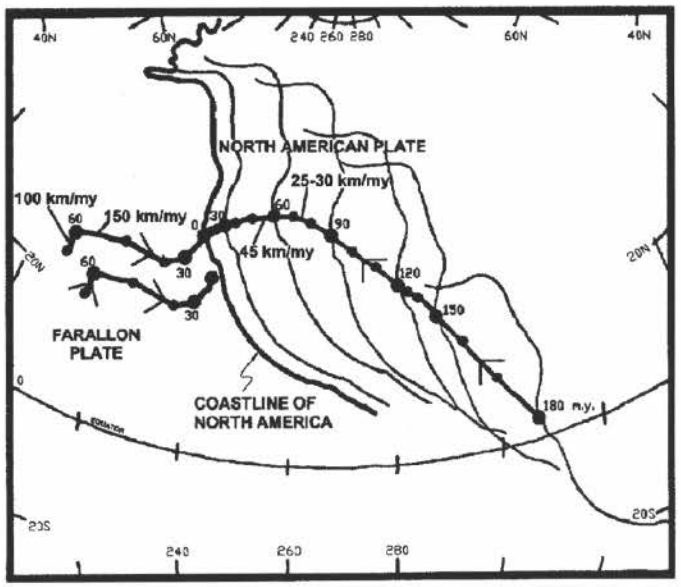


FIGURE 5. Trajectory of the North American and Farallon plates shown in 10 Ma intervals spanning the time of Laramide deformation (modified from Engebretson et al., 1984). Farallon plate direction and rate of movement are from Jurdy (1984) and are relative to a stationary North America. North American plate direction and rate of movement are relative to hotspots from Engebretson et al. (1984). Direction and rate of convergence change between 70 and 60 Ma in both plates.

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