Mesozoic–Paleogene structural evolution of the southern U.S. Cordillera as revealed in the Little and Big Hatchet Mountains, southwest New Mexico, USA

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ABSTRACT

A Mesozoic to Paleogene polyphase tectonic model presented here for the southern United States (U.S.) Cordillera provides new insight into style and timing of Mesozoic–Paleogene deformation and basin formation in the region south of the Colorado Plateau and Mogollon-Datil volcanic field. The model proposes reverse reactivation of Jurassic normal faults during Late Cretaceous Laramide shortening. It also recognizes late Paleogene east-west– and northwest-southeast–trending normal faults formed during a north-south extensional event that postdated Laramide shortening and preceded Neogene Basin and Range extension.

Late Jurassic to Early Cretaceous extension generated northwest-southeast normal faults that formed part of the Border rift system that extended from southern California to the northwestern Gulf of Mexico. The normal faults cut Mesoproterozoic basement rocks, and localized subsequent uplift of basement rocks during Late Cretaceous fault reactivation that formed northwest-southeast–trending Laramide uplifts of southwest New Mexico and southeastern Arizona. The Hidalgo uplift, reconstructed here from structural relations in the Little Hatchet and Big Hatchet Mountains of southwestern New Mexico, is bound by bivergent reverse faults that resulted from tectonic inversion of a Jurassic–Early Cretaceous graben. The Hidalgo uplift is flanked to the north by the Campanian to earliest Maastrichtian Ringbone basin, which accumulated synorogenic continental strata and basaltic andesite flows from ca. 75 to 70 Ma. The Ringbone basin was converted from a subsidizing basin in the Little Hatchet Mountains to a volcanic center by ca. 69 Ma, the emplacement age of an assemblage of shallow, subvolcanic intrusions termed the Sylvanian plutonic complex. The basin-involved structural style and yoked intermontane basin resemble other Laramide uplifts and basins in the Rocky Mountain Cordillera and refute alternative Laramide models of strike-slip faulting or regionally extensive horizontal thrust faults in southwestern New Mexico, the latter of which fail to account for basement-cored uplifts. A significant difference with the Rocky Mountain Laramide province is the size of the uplifts and basins and the close association of southern U.S. Cordilleran structures to nearby Late Cretaceous magmatic centers, which contributed to interstratified volcanic and volcaniclastic rocks in the basin fill.

Upper Eocene–Oligocene ignimbrites and volcaniclastic rocks of the Boot Heel volcanic field of southwestern New Mexico unconformably overlie Laramide syntectonic strata and bury eroded Laramide structures. The distribution of the Paleogene volcanic rocks in the Little Hatchet and Big Hatchet Mountains is in part controlled by synmagmatic east-west and northwest-southeast normal faults active from ca. 34 to 27 Ma, the age range of rhyolite dikes intruded along the faults. Two generations of intrusive rocks occupy these normal faults in the Little Hatchet Mountains: (1) older (ca. 34 Ma) phaneritic stocks and dikes in the central and southern parts of the range, and (2) younger (31–27 Ma) aphanitic latite and rhyolite dikes. East-west–trending faults and dikes are cut by north-south faults formed during Basin and Range extension. The late Eocene–early Oligocene north-south extension provides an important minimum age limit for Laramide shortening, which ended prior to ca. 34 Ma.

INTRODUCTION

A comprehensive synthesis of tectonic mechanisms for the Mesozoic–Cenozoic evolution of the western United States (U.S.) Cordillera requires consideration of the southern U.S. Cordillera. The southern U.S. Cordillera is defined here to encompass the region north of Mexico and south of the Colorado Plateau and Mogollon-Datil volcanic field, a geographic realm now occupied by the Basin and Range province of southeastern Arizona and southern New Mexico (Figs. 1 and 2). Prevailing models for the Late Cretaceous–Paleogene tectonic framework of North America commonly focus on the central Rocky Mountains of Colorado, Utah, Wyoming, and Montana, the Great Basin of Nevada and Utah (e.g., Dickinson, 2006), and the metamorphic core complexes of Arizona (e.g., Davis, 1980; Dickinson, 1991). Studies have extensively addressed various geologic aspects of the southern U.S. Cordillera and Rio Grande rift area, from Mesozoic deformation, magmatism, and sedimentation (e.g., Seager et al., 1986; Mack et al., 1988; Lawton and McMillan, 1999; Lucas and Lawton, 2000; Seager, 2004; Amato et al., 2017) to Paleogene magmatism and deformation (e.g., McIntosh and Bryan, 2000; Copeland et al., 2011); however, the Mesozoic to Paleogene kinematic history of southwestern New Mexico lacks a comprehensive geodynamic synthesis.
Figure 1. Late Jurassic (J) to Cretaceous (K) tectonic element map. Select tectonic elements of the western USA Cordillera consist of the following Mesozoic features: (1) approximate location of the Laurentian-Farallon trench plate boundary from Jurassic to Cretaceous; (2) regional extent of the Mesozoic Cordilleran magmatic arc and associated forearc region (Dickinson, 2006); (3) strike of the Sevier orogenic front (Dickinson, 2006); (4) location and extent of the Late Jurassic to earliest Late Cretaceous Mogollon Highlands and associated Border rift, with names of main rift basins (Lawton, 2004); and (5) orientation and location of major basement-cored Late Cretaceous Laramide uplifts (Cross, 1986; Saleeby, 2003; Seager, 2004). The boundaries of the flat slab corridor are modified from the interpreted extent of Laramide flat slab to very low-angle subduction of Weil and Young (2012). The Late Cretaceous Tarahumara arc is noted with italicized text. Extent of the Colorado Plateau in green. The location of the subregional study area is marked by the red rectangle (Fig. 3) and occupies the area referred to in text as the southern U.S. Cordillera.
Figure 2. Paleogene tectonic element map. Orange dashed lines denote the strike of the Paleogene magmatic arc and associated ages; arrows point in the direction of arc migration (Dickinson, 2002, 2006). The Juan de Fuca and Guadalupe plates were formerly contiguous and constituted the Farallon plate. By the Paleogene, flat slab and normal subduction transitioned to a period of slab rollback, which initiated the west-southwest migration of arc magmatism. The subregional map (Fig. 3) occupies the area between the late Eocene–Oligocene Mogollon-Datil and Boot Heel volcanic fields (McIntosh et al., 1992). Black circular to elliptical domains indicate the locations of Cenozoic (extensional) metamorphic core complexes. The relative location of the Mendocino and Rivera triple junctions, and associated ocean ridge and transform zones, are shown for ca. 25 Ma (Dickinson, 2002).
We define the Late Cretaceous to Paleogene southern U.S. Cordillera as a region characterized by narrow basement-cored uplifts and intermontane basins south of the Colorado Plateau. Laramide basement uplifts and adjacent basins in the southern U.S. Cordillera resemble those of the central Rocky Mountains; however, some striking differences exist. The uplift-to-basin wavelength of structures in southern New Mexico is ~50% smaller than contemporaneous structures in central Wyoming. Furthermore, magmatism accompanied shortening. Basement-involved shortening occurred inboard of the active Tarahumara volcanic arc in Sonora, Mexico (Fig. 1; González-León et al., 2011), and active plutonic centers occurred adjacent to the flanks of uplifts and volcanic complexes developed within Laramide intermontane basins.

Two contiguous mountain ranges in southwesternmost New Mexico, the Little Hatchet and Big Hatchet Mountains, referred to herein as the Hatchet ranges, contain well-exposed structural features that define a tectonic style representative of the southern U.S. Cordillera (Fig. 3). These ranges host a relatively complete stratigraphic section of Paleozoic to Mesozoic rocks, the thickest Laramide syntectonic stratigraphic section in southern New Mexico, a suite of dated Precambrian and Mesozoic rocks and Paleogene dikes and plutos, and extensive exposures of pre-Cenozoic structural features, strata, and magmatic systems (Zeller, 1970; Hodgson, 2000; Clinkscales and Lawton, 2014). We present geologic evidence demonstrating that structural relations in southern New Mexico are inconsistent with transient or wrench-style structures (e.g., Hodgson, 2000) and ramp-flat thrust geometries (e.g., Corbitt and Woodward, 1973; Drewes, 1988). Field and geochronologic data presented here also provide evidence for widespread, previously unrecognized east-west normal faults in the area that record a Paleogene, pre-Basin and Range synmagmatic extensional event that correlates with other Cordilleran extensional systems (e.g., Davis, 1980; Coney and Harms, 1984; Drewes, 1988). Field and geochronologic data presented here also provide evidence for widespread, previously unrecognized east-west normal faults in the area that record a Paleogene, pre-Basin and Range synmagmatic extensional event that correlates with other Cordilleran extensional systems (e.g., Davis, 1980; Coney and Harms, 1984; Drewes, 1988). Our results place new temporal and kinematic constraints on the Mesozoic to Paleogene evolution of the region south of the Colorado Plateau, a region critical to understanding timing and kinematic constraints on the development of intermontane basins. Laramide basement-involved shortening occurred inboard of the active Tarahumara volcanic arc in Sonora, Mexico (Fig. 1; González-León et al., 2011), and active plutonic centers occurred adjacent to the flanks of uplifts and volcanic complexes developed within Laramide intermontane basins.

A transition from post-rift thermal subsidence to foreland basin subsidence occurred by late Albian–Cenomanian time. This change in basin dynamics is recorded by increased tectonic subsidence rates (Mack, 1987; Clinkscales and Lawton, 2014), changes in detrital provenance signaled by volcanic-lithic compositions, and systematic differences in paleocurrents and facies from lower and upper Cretaceous rocks (Mack et al., 1986; Machin, 2013). In the Little Hatchet Mountains of southwestern New Mexico, the change from rift basin to foreland basin is recorded by the deposition of more than 1400 m of fluvial and marginal marine strata of the Mojado Formation and Mancos Shale (e.g., Lucas and Lawton, 2006). Siliciclastic strata of the Mojado Formation and correlative Beartooth Quartzite in the Burro Mountains and Cookes Range (Fig. 3) record a volcanic and recycled ocean source terrane with east-directed paleocurrents sourced from a retroarc fold-thrust belt to the west (Mack, 1987; Machin, 2013). By mid-Cenomanian time, the foreland basin in southern New Mexico was contiguous northward with the Cordilleran foreland basin of northern New Mexico, Colorado, and Utah.

GEOLOGIC BACKGROUND

The principal structural belts defining the Jurassic to Paleogene paleogeography of the west-central U.S. Cordillera and Rocky Mountains (present-day California, Colorado, Montana, Nevada, Utah, and Wyoming) broadly consist of the following tectonic elements, from east to west (Fig. 1): (1) basement-involved Laramide block uplifts and flanking intermontane basins (Dickinson and Snyder, 1978; Dickinson et al., 1988; Lawton, 2008); (2) a north-south frontal thrust belt and associated foreland basin of the Sevier orogen (Lawton, 1994; DeCelles and Coogan, 2008); (3) an extensive orogenic plateau and hinterland, named the Nevadaplano (DeCelles, 2004); and (4) the Sierra Nevada volcanic arc and forearc region (Dickinson, 2006). To the south of the central Rocky Mountains, in present-day Arizona and southwestern California, the Sevier fold-thrust belt terminated along strike near the northwestern extent of the Mogollon Highlands. These highlands represent the northern rift shoulder of the Late Jurassic to Early Cretaceous Border rift system, which included the McCoy, Bisbee, Chihuahua, and Sabinas basins and ultimately connected to the nascent Gulf of Mexico basin (Bilodeau, 1982; Dickinson et al., 1986; Lawton and McMillan, 1999; Stern and Dickinson, 2010; Fig. 1).

Late Jurassic through mid-Late Cretaceous deformation varied along strike in the southwestern U.S., with shortening in the Basin and Range region (Sevier orogen) passing southward to extensional deformation in the southern U.S. Cordillera. A Late Jurassic to Early Cretaceous belt of extensional basins, collectively termed the Border rift, trended northwest-southwest from present-day southern California, southern Arizona, and New Mexico (Fig. 4), and extended into northeastern Mexico (Dickinson et al., 1986; Lawton and McMillan, 1999; Mickus et al., 2008; Spencer et al., 2011). Uplifted rift blocks along the northern edge of the rift system formed the Mogollon Highlands, a significant drainage divide (e.g., Bilodeau, 1988; Lawton et al., 2014) between the southern end of the Cordilleran foreland basin and Border rift. Upper Jurassic to lower Cretaceous continental, marginal-marine, and shallow-marine deposits and associated magmatism record active crustal extension to post-rift thermal subsidence (Garrison and McMillan, 1999; Mauel et al., 2011; Spencer et al., 2011). Proposed mechanisms for rifting include extension or transform motion associated with the opening of the Gulf of Mexico (Bilodeau, 1982) and extension due to backarc (Lawton and McMillan, 1999; Dickinson and Lawton, 2001) or interarc processes (Stern and Dickinson, 2010) related to rollback of the Farallon and Mezcalera plates (Dickinson and Lawton, 2001).
Figure 3. Geologic map of southwestern New Mexico (scale 1:500,000) and southeastern Arizona (scale 1:1,000,000). Northwest-southeast Laramide structures and their inferred positions across ranges are dashed and correlate to exposed structural and stratigraphic relationships, well penetrations, and subregional extrapolations (Seager, 2004). The names of the principal Laramide uplifts and basins are italicized. Note the dominant rock exposures in the region consist of Paleogene–Neogene volcanic rocks (pink). The Little and Big Hatchet Mountains (study area) offer a unique exposure of Paleozoic and Mesozoic rocks along a north-south transect offset by various northwest-southeast Laramide structures, and expose the roots of the Hidalgo uplift and syn-Laramide strata of the Ringbone Basin. Geologic map of New Mexico from Green and Jones (1997); geologic map of Arizona is from Richard et al. (2000). The geographic information system map format was made available through Ludington et al. (2005). Labeled ranges include Animas Hills (AH), Animas Mountains (AN), Big Hatchet Mountains (BH), Black Range (BR), Burro Mountains (BM), Chiricahua Mountains (CH), Caballo Mountains (CM), Cooke Range (CR), Cedar Mountain Range (CD), East Potrillo Mountains (PM), Florida Mountains (FL), Little Hatchet Mountains (LM), Organ Mountains (OM), Peloncillo Mountains (PL), Pyramid Mountains (PY), Robledo Mountains (RM), San Andres Mountains (SAI), Silver City Range (SCR), Sierra Rica Mountains (SR), Tres Hermanas Mountains (TH), and Victorio Mountains (VM).
Figure 4. Lower–lowermost upper Cretaceous subcrop map. Colored areas refer to the subcrop relationships for lower–lowermost upper Cretaceous rocks in the southern New Mexico and southeastern Arizona. Dashed faults refer to present-day location of major normal faults of the Border rift, defined by subcrop relationships and major Laramide reverse faults. The approximate limit of lower Cretaceous Bisbee Group rocks is indicated by dashed line to the north. Modified from Lawton (2000). Refer to Figure 3 caption for sources on background geologic maps.
Late Cretaceous to Eocene Laramide orogenesis involved the breakup of the Cordilleran foreland by uplift of basement-involved blocks along reverse and thrust faults (Dickinson and Snyder, 1978; Cross, 1986; Seager and Mack, 1986; Dickinson et al., 1988; Mack and Clemons, 1988). Geotectonic models invoke flat slab subduction as the driving mechanism for far-field Laramide deformation (Dickinson and Snyder, 1978; English et al., 2003), which occurred 700–1500 km from the trench, and a general null in arc magmatism along the flat slab corridor (Saleeby, 2003). Factors controlling the shallowing of the Farallon plate include the subduction of younger, buoyant oceanic crust and/or subduction of an aseismic ridge or thick oceanic plateau (Henderson et al., 1984; Liu et al., 2010; Heller and Liu, 2016; Copeland et al., 2017).

Laramide uplifts consist of thick-skinned, basement-involved features that generally flank intermontane basins dominated by alluvial, fluvial, and lacustrine deposits. The orientation and distribution of many Laramide uplifts in the central Rocky Mountains are inferred to be controlled by antecedent structural lineaments (e.g., Marahak et al., 2000; Stone, 2002). Similarly, Jurassic normal faults of the Border rift system, locally the Bisbee basin in New Mexico and Arizona, were reactivated as reverse faults during Laramide shortening (Lawton, 2000; Bayona and Lawton, 2003).

Laramide uplifts and basins in southern New Mexico are oriented northwest-southeast and bounded by reverse faults that generally verge northeast (Fig. 3; Seager, 2004) and contain upper Cretaceous to Paleogene continental and volcanic deposits (Basabilvazo, 2000; Seager et al., 1997; Lawton, 2008; Jennings et al., 2013; Amato et al., 2017). The distribution of these uplifts and basins is rendered uncertain by Cenozoic basin fill that extensively buries the Laramide syntectonic rocks and structures; moreover, structural overprinting by multiple deformation episodes also confounds interpretation of the kinematic history. Nevertheless, exposures are sufficient to establish the structural and depositional boundaries of Laramide uplifts and basins (Seager et al., 1997; Seager, 2004; Clinkscales and Lawton, 2014). Early studies in the region characterized shortening structures as ramp-flat thrust faults akin to a thin-skinned deformation style similar to contemporaneous structures in the Sevier orogenic belt of the U.S. Cordillera (Corbitt and Woodward, 1973; Lawton, 1985; DeCelles, 2004). Later studies in the northern Little Hatchet Mountains interpreted Laramide deformation as a thick-skinned deformation event that occurred in two discrete pulses, a Late Cretaceous shortening event accompanied by basement uplift and later Eocene transcurrent deformation that reactivated the former basement-involved faults (Hodgson, 2000). The two pulses were defined in the Little Hatchet Mountains on the basis of inferred discrete Campanian–Maastrichtian and Eocene ages for the Laramide syntectonic Ringbone and Skunk Ranch Formations, respectively (e.g., Lawton et al., 1993; Basabilvazo, 2000). Late Cretaceous deformation was attributed to southwest-northeast shortening, whereas Eocene deformation was attributed to strike-slip displacement on basement-involved faults that formed a full positive flower structure, consisting of northeast-verging structures in the Little Hatchet Mountains and southwest-verging structures in the Big Hatchet Mountains (Seager, 1983, 2004). Recent studies integrating structural-stratigraphic relations with U-Pb dating of syn-Laramide clastics and interbedded tuffs demonstrate that no significant hiatus occurs between the Ringbone and Skunk Ranch Formations. Instead, the unconformity represents a progressive unconformity along intrabasinal thrust faults with no evidence of Paleogene deposition and major shift in Laramide kinematics (Clinkscales and Lawton, 2014).

Late Cretaceous deformation in southern New Mexico occurred nearly coeval with northeastward migration of arc magmatism from coastal Sonora, Mexico, to southern New Mexico from ca. 115 to 69 Ma. This geographic shift in arc volcanism is recorded by (1) ca. 115–92 Ma volcanic rocks and plutons of the Peninsular Ranges in Baja California and coastal Sonora (Wetmore et al., 2003); (2) post-90 Ma volcanioclastic and plutonic rocks of the Tarahumara arc in northern Sonora, Mexico (González-León et al., 2011); and (3) upper Cretaceous volcanic rocks and plutons in southwestern New Mexico (e.g., Hidalgo Formation and Sylvanite plutonic complex, discussed herein). Late Cretaceous to Paleogene magmatism in southern New Mexico is argued to be related to three magmatic arc episodes (e.g., McMillan, 2004) have occurred from 76 to 70 Ma, 61 to 57 Ma, and 46 to 40 Ma (Amato et al., 2017). Igneous rocks bracketed for the oldest episode, between ca. 76 and 70 Ma, crop out within and near the Little and Big Hatchet Mountains, including exposures in the central and northern Little Hatchet Mountains, Lordsburg, the Burro Mountains, Silver City area, and Animas Hills (Fig. 3). Northeastward migration of Cretaceous magmatism and volcanism is inferred as a result of progressive shallowing of the Farallon plate (e.g., Coney and Reynolds, 1977).

The Paleogene was a period of major tectonic reconfiguration from shortening to extension, accommodated by changing convergent plate kinematics along western Laurentia (Coney and Reynolds, 1977). Prevailing models for post-Sevier and post-Laramide deformation and magmatism invoke Cordilleran-scale extension (Atwater, 1970; Coney and Harms, 1984) and onset of silicic magmatism (e.g., McIntosh et al., 1992; McIntosh and Bryan, 2000). Regionally diachronous crustal extension occurred roughly synchronously with a migration of arc magmatism south-southwestward from Idaho to Nevada across the Great Basin and westward from New Mexico across Arizona and Sonora, Mexico (Gans, 1997; Dickinson, 2006). These arc belts nearly converged ca. 20 Ma at an amagmatic corridor west of the Colorado Plateau and east of the incipient Mendocino triple junction and early San Andreas fault system (Dickinson, 2002). The Boot Heel volcanic field in southern New Mexico (Fig. 2) is associated with the westward migration of arc volcanism through the southern U.S. Cordillera and is recorded by thick rhyolite to rhyodacite ignimbrites and lavas erupted during two discrete phases, from 35.2 to 32.7 Ma and 27.6 to 26.8 Ma (McIntosh and Bryan, 2000). An ignimbrite in the Little Hatchet Mountains with a 40Ar/39Ar (sanidine) age of 32.6 ± 0.16 Ma was emplaced during the first magmatic pulse (McIntosh and Bryan, 2000).
Methods

Compiled geologic maps (Figs. 5 and 6) for the ranges include our geological mapping in the Little Hatchet Mountains, conducted at scales of 1:10,000 and 1:24,000, and evaluation of previously published geological maps in both ranges (Zeller, 1970; Drewes, 1991; Hodgson, 1991; 2000). Cross-section construction was based on projected map contacts, dip measurements, and local measured sections and aided by use of 2D Move (https://www.mve.com/software/move) software (Fig. 7). Stratigraphic nomenclature, age, and principal rock types are summarized in Figure 8. Newly published geochronology from the Little Hatchet Mountains includes U-Pb zircon ages for five samples analyzed by laser ablation–multicollector–inductively coupled–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center (Tucson, Arizona). Specifications on testing sample reproducibility, accuracy, analytical procedures, and uncertainties with LA-MC-ICP-MS at the Arizona LaserChron center were described in more detail elsewhere (Gehrels et al., 2008; Gehrels, 2012). We also cite unpublished 40Ar/39Ar ages from rhyolite dikes (Cleary, 2004) in the central domain of the Little Hatchet Mountains (Table 1). Previously published and unpublished 40Ar/39Ar ages were recalculated using the ArArCALC program (Koppers, 2002).

Geochronology

Unpublished U-Pb geochronologic data that provide new insight on ages of faults, plutonism, and structural relations in the Little Hatchet Mountains are described here. U-Pb geochronologic data for samples analyzed as part of this study are provided in the Supplemental Item. A metamorphosed alkali feldspar granite (14GP03) collected adjacent to the Granite Pass–Windmill thrust system in the southern Little Hatchet Mountains (Fig. 6) yielded a weighted mean age of 1090 ± 15 Ma (Fig. 9A); mean square of weighted deviates, MSWD = 0.34, n = 5). The rock consists of a granular mosaic of orthoclase (60%), quartz (30%), and plagioclase (10%) with clots of intergrown biotite and hematite that represent an altered ferromagnesian mineral, perhaps hornblende, and yield a color index of ~8. This is the first reported occurrence of Proterozoic basement north of Granite Pass in the Little Hatchet Mountains. An aplite granite dike (1.1.30.10) collected near Granite Pass in the southern Little Hatchet Mountains yielded a weighted mean age of 1085 ± 13 Ma (Fig. 9B; MSWD = 0.29, n = 13). Aplite dikes intrude a rapakivi granite host and are of similar age, as indicated by overlapping U-Pb zircon ages (1077 ± 18 Ma; Amato and Mack, 2012), and can be differentiated from the host granite by a finely crystalline groundmass with abundant quartz phenocrysts, and lack of K-feldspar megacrysts. Precambrian aplite dikes are almost exclusively composed of quartz, orthoclase, and finely crystalline biotite. A quartz monzonite sample from the Sylvanite plutonic complex (Fig. 5) yielded a U-Pb zircon weighted mean age of 89 ± 1 Ma (Fig. 9C; MSWD = 0.80, n = 44). The Sylvanite plutonic complex is composed of diorite, monzonite, and quartz monzonite that intrude Jurassic to Cretaceous strata south of the Copper Dick fault (Zeller, 1970). Monzonite and quartz monzonite rocks are phaneritic with medium-grained crystals of elongate plagioclase, orthoclase, amphibole, and local quartz. Diorite intrusions contain minerals similar to those of the monzonite rocks but tend to have a darker anphatic groundmass (Zeller, 1970). Diorite indicated on the geologic map of Zeller (1970) is Jurassic basalt intruded by the Sylvanite plutonic complex (Lawton and Harrigan, 1998; Clinkscales and Lawton, 2014).

An alkali feldspar granite collected from a <10 m² fault block along the western trace of the Copper Dick fault yielded a U-Pb zircon age of 34 ± 1 Ma (Fig. 9D; MSWD = 0.18, n = 11). Compositional and texturally similar granites crop out along both segments of the Copper Dick fault. These granite exposures do not exceed 10 m² and consist of equigranular monocrystalline quartz and orthoclase phenocrysts, microcrystalline plagioclase, and subordinate biotite. The granite along the fault is sheared and brecciated, indicating emplacement during protracted fault movement. Previous maps interpreted these granite intrusions along the Copper Dick fault as Precambrian (Hodgson, 2000) or Cretaceous–Paleogene (Zeller, 1970) fault slivers; our U-Pb zircon age data confirm a latest Eocene to early Oligocene age.

A porphyritic granite with finely crystalline groundmass of quartz, plagioclase, and orthoclase yielded a weighted mean U-Pb age of 29 ± 1 Ma (Fig. 9E; MSWD = 0.74, n = 8). The granite comprises nearly equal proportions and phenocrysts of quartz with embedded rims (7%–10%), plagioclase (10%), and orthoclase (20%), and forms a conspicuous east-west–trending dike as much as 40 m wide in the southern part of the Little Hatchet Mountains (Zeller, 1970). The dike resembles the Granite Pass Granite in texture and mineral content. The age is statistically younger than a K-feldspar 40Ar/39Ar age of 3.27 ± 0.18 Ma for the Granite Pass pluton recalculated from a legacy age of 3.32 ± 0.16 Ma reported by Channell et al. (2000; Table 1).

Structural Relations of the Hatchet Ranges

The Little Hatchet Mountains constitute a north-south horst bounded by north-trending normal faults. The topography of the range and mapped fault relationships indicate that the bounding faults are discontinuous along strike with fault terminations giving way to relay or transfer zones similar to those described by Faulds and Varga (1998). The Big Hatchet Mountains, oriented roughly north-south to northwest-southeast, are separated from the Little Hatchet Mountains by surficial deposits at Hatchet Gap (Fig. 5); however, northwest-southeast faults exposed in the Big Hatchet Mountains and on its northeastern flank impart a control on the topography of the range and may be related to extension that predated east-west Basin and Range extension.

North-south faults demonstrably offset both northwest-southeast reverse and thrust faults and east-west and northwest-southeast normal faults. East-west– and northwest-southeast–trending normal faults displace Laramide shortening structures. The two sets of normal faults serve to expose a variety of Laramide structural levels discussed in the text.
Figure 5. Bedrock geologic map of Little and Big Hatchet Mountains. Major faults discussed in text are labeled. Geologic map of the Little Hatchet Mountains is adapted and modified from Zeller (1970), Hodgson (2000), and Clinkscales and Lawton (2014). The geology of the Big Hatchet Mountains is simplified from Drewes (1991) and illustrates the major structural elements. Cross sections are shown in Figure 7.
Figure 6. Geologic map of southern Little Hatchet Mountains near Granite Pass. The two principal reverse faults that define the northern flank of the Hidalgo uplift, the Granite Pass and Windmill faults, are present in the map area. Both faults are defined by ca. 1.1 Ga igneous rocks in hanging wall, substantiated by U-Pb zircon ages with sample locations shown by red dots. A ca. 29 Ma granite dike crosscuts the Windmill fault. Map location is shown in Figure 5. USGS—U.S. Geological Survey; UTM—Universal Transverse Mercator; NAD 27—North American Datum 1927.
Little Hatchet Mountains

We define three structural domains in the Little Hatchet Mountains (Fig. 10): (1) a southern domain from Hatchet Gap north to the Windmill fault; (2) a central domain between the Windmill fault on the south and the Copper Dick fault on the north; and (3) a northern domain that extends from the Copper Dick fault to the southernmost Coyote Hills. The exposed strata (Fig. 8) consist of (1) fault-bound horses of upper Paleozoic rocks; (2) upper Jurassic and lower to upper Cretaceous rocks of the Bisbee Group, including the Broken Jug (formerly Broken Jug Limestone of Lasky, 1947), Hell-to-Finish, U-Bar, and Mojado Formations (Lucas et al., 2001), and Mancos Shale; (3) upper Cretaceous synorogenic Laramide strata of the Ringbone and Skunk Ranch Formations and volcanic Hidalgo Formation; and (4) upper Eocene to Oligocene ignimbrites and interbedded epiclastic strata.

Southern Domain

The southern domain consists of faulted Proterozoic igneous rocks and Paleozoic strata. Rapakivi granite and aplitic dikes ca. 1.1 Ga (Amato and Mack, 2012; this study) are exposed in the southernmost Little Hatchet Mountains and at Hatchet Gap. The northwest-southeast Hatchet Gap normal fault juxtaposes footwall Precambrian rocks and lower Paleozoic strata against Pennsylvania Horquilla Limestone with an estimated fault throw of 2200 m, calculated on the basis of omitted lower Paleozoic strata (Fig. 7). Near Granite Pass, Precambrian igneous rocks are present in the hanging wall of both the Granite Pass and Windmill faults. The Granite Pass fault emplaces Precambrian rocks against overturned Horquilla Limestone. The minimum throw on the Granite Pass fault, estimated from the cumulative thickness of lower Paleozoic strata (e.g., Zeller, 1965; Drewes, 1991), is ~2000 m.
Figure 8. Generalized stratigraphic columns of Big (left) and Little (right) Hatchet Mountains. The Big Hatchet Mountains expose the most complete Paleozoic section in the region (Zeller, 1965; Drewes, 1991), whereas the Little Hatchet Mountains expose an extensive upper Jurassic to lower-upper Cretaceous section with the thickest known Laramide synorogenic deposits in the southern U.S. Cordillera (e.g., Lucas and Lawton, 2000). The Laramide synorogenic Hidalgo Formation is not illustrated in the Little Hatchet Mountains section. An incomplete section of lower to upper Cretaceous (Bisbee Group) rocks is exposed in the southernmost Big Hatchet Mountains and only partial exposures are present in the range, so no individual thicknesses are denoted. Refer to Little Hatchet Mountains column for Bisbee Group formation thicknesses. No upper Jurassic rocks have been identified or previously recognized (e.g., Drewes, 1991; Lawton and Harrigan, 1998) in the Big Hatchet Mountains.
**TABLE 1. IGNEOUS ROCK AGES, LITTLE HATCHET MOUNTAINS**

<table>
<thead>
<tr>
<th>Unit description, sample ID</th>
<th>Age</th>
<th>System</th>
<th>Location*</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Alkali feldspar granite, sample 14GP03</td>
<td>1090 ± 15 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.784533, –108.467050</td>
<td>This study</td>
</tr>
<tr>
<td>Aplite dike in rapakivi granite, sample 1.30.10.1</td>
<td>1085 ± 13 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.764040, –108.456490</td>
<td>This study</td>
</tr>
<tr>
<td>Tuff in lower Mancos Shale, sample 11BQ18</td>
<td>972 ± 1.6 Ma (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.863691, –108.462991</td>
<td>Machin (2013)</td>
</tr>
<tr>
<td>Skunk Ranch Formation (middle member), ash-fall tuff, sample 1.5.27.10</td>
<td>70.38 ± 0.48 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.852063, –108.482052</td>
<td>Jennings et al. (2013)</td>
</tr>
<tr>
<td>Skunk Ranch Formation (middle member), ash-fall tuff, sample 10GJ-2</td>
<td>70.63 ± 0.70 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.864879, –108.484800</td>
<td>Jennings et al. (2013)</td>
</tr>
<tr>
<td>Skunk Ranch Formation (middle member), ash-fall tuff, sample 10GJ-1</td>
<td>71.44 ± 0.53 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.865032, –108.483401</td>
<td>Jennings et al. (2013)</td>
</tr>
<tr>
<td>Ringbone Formation (upper member), ash-fall tuff, sample 15.8.28.10</td>
<td>73.31 ± 0.71 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.873648, –108.485872</td>
<td>Clinkscales and Lawton (2014)</td>
</tr>
<tr>
<td>Ringbone Formation (middle member), ash-fall tuff, sample 10.11.22.10</td>
<td>73.41 ± 0.97 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.891571, –108.476051</td>
<td>Clinkscales and Lawton (2014)</td>
</tr>
<tr>
<td>Hidalgo Formation (Hidalgo Volcanics of Zeller, 1970), sample NM-679</td>
<td>71.44 ± 0.38 (legacy)</td>
<td>40Ar/39Ar hornblende</td>
<td>31.934617, –108.465517</td>
<td>Lawton et al. (1993);</td>
</tr>
<tr>
<td>Hidalgo Formation (Hidalgo Volcanics of Zeller, 1970), sample HDV-127</td>
<td>71.61 ± 0.44 (Earthtime recalculation)</td>
<td>40Ar/39Ar hornblende</td>
<td>31.936917, –108.496150</td>
<td>Young et al. (2000)</td>
</tr>
<tr>
<td>Sylvanite intrusive complex (quartz monzonite), sample 16.11.7.10</td>
<td>68.76 ± 0.61 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.857377, –108.477121</td>
<td>This study</td>
</tr>
<tr>
<td>Diorite intruding Eureka intrusive complex, sample EUREKA</td>
<td>35.5 ± 1.7 (legacy)</td>
<td>40Ar/39Ar groundmass</td>
<td>north of Hidalgo fault; precise location unknown</td>
<td>Channell et al. (2000)</td>
</tr>
<tr>
<td>Granite in Copper Dick fault zone, sample 2.13.1.10</td>
<td>35.96 ± 1.7 (Earthtime recalculation)</td>
<td>40Ar/39Ar groundmass</td>
<td>31.850324, –108.484868</td>
<td>This study</td>
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<td>Ignimbrite tuff (Gillespie Tuff), sample 682</td>
<td>33.8 ± 0.7 (weighted mean; 2σ uncertainty); 33.1 ± 2.8 (lower intercept; 2σ uncertainty)</td>
<td>U-Pb, zircon</td>
<td>31.856000, –108.505000</td>
<td>McIntosh and Bryan (2000)</td>
</tr>
<tr>
<td>Granite at Granite Pass, sample GP-23</td>
<td>32.62 ± 0.16 (legacy)</td>
<td>40Ar/39Ar sanidine</td>
<td>31.901000, –108.505000</td>
<td>Young et al. (2000)</td>
</tr>
<tr>
<td>Granite at Granite Pass, sample GP-23</td>
<td>32.33 ± 0.16 (legacy, weighted mean of biotite and potassium feldspar ages)</td>
<td>40Ar/39Ar biotite and potassium feldspar</td>
<td>Granite Pass; precise location unknown</td>
<td>Channell et al. (2000)</td>
</tr>
<tr>
<td>East-west rhyolite dike, sample SPLD-5</td>
<td>32.74 ± 0.16 (Earthtime recalculation)</td>
<td>40Ar/39Ar biotite and potassium feldspar</td>
<td>31.825083, –108.430733</td>
<td>Cleary (2004) (appendix B**))</td>
</tr>
<tr>
<td>Northeast-southwest granite dike, sample 14GP01</td>
<td>31.61 ± 0.57 (Earthtime recalculation)</td>
<td>40Ar/39Ar hornblende</td>
<td>31.826033, –108.431067</td>
<td>Cleary (2004) (appendix B**))</td>
</tr>
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<td>East-west rhyolite dike, sample SPLD-4</td>
<td>26.9 ± 0.4 (weighted mean; 2σ uncertainty)</td>
<td>U-Pb zircon</td>
<td>31.786733, –108.467900</td>
<td>This study</td>
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<td>East-west rhyolite dike, sample SPLD-1</td>
<td>28.18 ± 0.97 (legacy)</td>
<td>40Ar/39Ar groundmass</td>
<td>31.841017, –108.432550</td>
<td>Cleary (2004) (appendix B**))</td>
</tr>
<tr>
<td>East-west rhyolite dike, sample SPLD-1</td>
<td>27.15 ± 0.98 (Earthtime recalculation)</td>
<td>40Ar/39Ar groundmass†</td>
<td>31.837767, –108.430767</td>
<td>Cleary (2004) (appendix B**))</td>
</tr>
</tbody>
</table>

†No plateau age calculated; stated age is total gas age.  
§Approximate location: Sample collected in section 23, Township 29 south, Range 16 west in southern Little Hatchet Mountains.  
Figure 9. Weighted mean age plots. MSWD—mean square of weighted deviates. (A) Alkali feldspar granite at Windmill fault. (B) Aplite granite at Granite Pass fault. (C) Quartz monzonite from Sylvanite plutonic complex. (D) Alkali feldspar granite along Copper Dick fault. (E) Porphyritic granite dike that crosscuts Windmill fault. Sample locations for A, B, and E are shown in Figure 6 and for C and D are shown in Figure 10. Plots were generated with Isoplot (Ludwig, 2003).
The Windmill fault emplaces Precambrian rocks against the lower Cretaceous Mojado Formation (Figs. 5 and 6). A subsidiary splay of the Windmill fault (Fig. 6) juxtaposes the Earp Formation in the hanging wall of the splay against Mojado Formation in the footwall. The minimum throw on the Windmill fault, estimated from the cumulative thickness of Paleozoic strata to the upper part of the Mojado Formation, assuming an absence of Jurassic Broken Jug strata due to southward pinchout of Jurassic beds, is ~4200 m. Despite an absence of unambiguous evidence for subsequent extensional reactivation along the Windmill fault, its orientation parallel to a nearby northwest-southeast normal fault suggests that the observed stratigraphic displacement is a minimum.

Central Domain

North of Granite Pass, upper Jurassic to Cretaceous strata of the Bisbee Group (Lawton and Olmstead, 1995; Lucas and Lawton, 2005) comprise an extensive south-southwest-dipping panel that dominates the central domain. The central domain contains the only recognized exposures of Jurassic Broken Jug Formation in southwestern New Mexico (Fig. 3; Lawton and Olmstead, 1995), but correlative upper Jurassic strata are present in the Chiricahua Mountains of southeast Arizona (Figs. 3 and 4; Lawton and Olmstead, 1995).
adjacent to the eastern segment of the Copper Dick fault. The Bisbee Group is intruded by the Late Cretaceous Sylvanite Complex, near which the strata are extensively thermally metamorphosed. Bisbee strata are locally displaced by minor east-west, west-northwest-east-southeast-trending normal faults with <10 m of offset, rhyolite dikes, and thrust faults. Conjugate west-northwest–east-southeast and east-northeast–west-southwest rhyolite dikes that intrude Bisbee Group strata yielded $^{40}$Ar/$^{39}$Ar ages between 32 and 27 Ma (Table 1; Cleary, 2004). Paleozoic strata that underlie the Broken Jug Formation are locally exposed adjacent to the eastern segment of the Copper Dick fault.

**Northern Domain**

The northern domain of the Little Hatchet Mountains is bounded on the south by the Copper Dick fault and on the north by a prominent northwest-southeast normal fault that juxtaposes Mojado Formation against Oligocene ignimbrites of the Coyote Hills (Fig. 5). The west-east Copper Dick fault has a north dip of ~60° and a down-to-the-north minimum stratigraphic displacement along its western segment of 3000 m, estimated from offset lower Cretaceous strata. Total offset along the eastern segment of the fault is accommodated across two east-west normal faults (Fig. 7A) and across one dominant fault on its western segment (Fig. 7B).

The synorogenic the Ringbone and Skunk Ranch Formations (Fig. 8) occupy the northern domain of the Little Hatchet Mountains (Basabilvazo, 2000; Hodgson, 2000) and unconformably overlie Bisbee Group strata and a local exposure of Mancos Shale (Lucas and Lawton, 2005). The Ringbone and superjacent Skunk Ranch Formations consist of (1) alluvial and fluvial conglomerates containing unmetamorphosed clasts of Bisbee Group and Paleozoic rocks that record an unroofing sequence of Cretaceous to Paleozoic strata (Clinkscales and Lawton, 2014); (2) braided fluvial volcanic-lithic sandstones; and (3) lacustrine rocks intercalated with ash-fall tuffs (Lawton et al., 1993; Jennings et al., 2013; Clinkscales and Lawton, 2014). Bisbee Group strata are exposed in the west-plunging Howells Well syncline and as discontinuous fault-bounded slivers along thrust faults. Isolated fault blocks (~10 m$^2$) of mylonitic U-Bar Formation limestone crop out along the Copper Dick fault and commonly consist of marble with granular texture and local foliation with an average 73° (NE) strike, subparallel to the Copper Dick fault. Fault sheared granite, in domains which rarely exceed 10 m$^2$, is present along both segments of the Copper Dick fault zone. One of these granite exposures was dated at 34 Ma (Fig. 9D).

The northern structural domain south of the Hidalgo fault can be further divided into western and eastern sectors across the north-trending Livermore Spring fault. The Livermore Spring fault displaces the western segment of the Copper Dick fault southward relative to its eastern segment in the footwall of the Livermore Spring fault. The strike separation between the western and eastern traces of the Copper Dick fault is likely augmented by oblique slip along the Livermore Spring fault, as recorded by fault slickenlines (53°, 223°, rake = 37°).

The east-west trending Bull Canyon graben lies between the Copper Dick fault to the south and the Bull Canyon fault to the north. The graben is offset at the Livermore Spring fault, with the antithetic graben-bounding faults of the footwall more closely spaced than in the western hanging wall. East of the Livermore Spring fault, the Bull Canyon graben contains a syncline that includes Ringbone Formation unconformable upon a narrow (~100 m) exposure of Mancos Formation. West of the Livermore Spring fault, the Skunk Ranch Formation directly overlies the U-Bar Formation. No Ringbone Formation is present west of the fault, and U-Bar limestone boulders locally dominate the basal conglomeratic beds of the Skunk Ranch Formation. Upper Eocene–Oligocene volcanic rocks unconformably overlying the Skunk Ranch Formation contain a basal lag of Skunk Ranch boulders. North of the Bull Canyon fault and the Mojado thrust fault, the Skunk Ranch Formation overlies the Ringbone Formation (Basabilvazo, 2000). Volcanic and volcanioclastic strata in the Bull Canyon graben constitute the thickest preserved Paleogene section in the Little Hatchet Mountains. No Paleogene rocks are exposed east of the Livermore Spring fault or south of the Copper Dick fault.

The segment of the Livermore Spring fault between the Bull Canyon and Copper Dick faults displays older-on-younger stratigraphic separation despite the fault’s normal displacement. Hanging wall U-Bar Formation is juxtaposed against Ringbone Formation, leading previous workers to interpret this segment of the Livermore Spring fault as a thrust fault (Zeller, 1970), potentially related to Eocene transpression along the Copper Dick fault (Hodgson, 2000). Normal offset on the Livermore Spring fault is unambiguous north and south of this central segment; moreover, the southern continuation of the fault represents the western range-bounding fault, indicating its young age (Fig. 5).

The folded Howells Ridge thrust fault parallels both limbs of the Howells Well syncline and displays striking changes in stratigraphic separation along strike. On the north flank of the syncline, the fault trends northwest-southeast and is offset by the north-south Beacon Hill normal fault. West of the Beacon Hill fault, the Howells Ridge fault juxtaposes the U-Bar Formation over the Ringbone Formation, displaying unambiguous reverse separation (Fig. 7B), whereas to the east, the fault juxtaposes the upper part of the U-Bar Formation over the Hell-to-Finish and lower U-Bar Formations and thus displays normal separation. Laramide synorogenic strata are absent east of the Beacon Hill fault, except for a thin, local exposure of lowermost Ringbone Formation, which unconformably overlies the Hell-to-Finish Formation adjacent to the fault (Basabilvazo, 2000), indicating that Hell-to-Finish likely underlies Ringbone Formation west of the Beacon Hill fault (Fig. 7B). The Ringbone and Hidalgo formations crop out west of the Beacon Hill fault in an asymmetric syncline (Fig. 5).

The northern domain can be further divided at the NW-trending Hidalgo fault, a prominent northeast-verging reverse fault that juxtaposes Bisbee and Ringbone Formation strata against the Hidalgo Formation. Along the central to eastern trace of the Hidalgo fault, the Hell-to-Finish Formation wasemplaced
over upper Cretaceous Hidalgo Formation, but west of the Beacon Hill fault, the Ringbone Formation is thrust over the Hidalgo Formation.

The Hidalgo Formation crops out extensively north of the Hidalgo fault. North of the Hidalgo fault, the Bisbee Group and Ringbone Formation are limited to the northeastern part of the range, where they are folded into an anticline-syncline pair adjacent to the Ringbone thrust fault (Fig. 5; Zeller, 1970; Hodgson, 2000). The Hidalgo Formation unconformably overlies the Hell-to-Finish, U-Bar, and Ringbone formations and is intruded by Oligocene diorite dikes of the Eureka intrusive complex (Channell et al., 2000). The Ringbone Formation unconformably overlies the U-Bar Formation in the hanging wall of the Ringbone fault, which emplaces Ringbone, Hell-to-Finish, and U-Bar strata over the Mojado Formation. The absence of the Mojado Formation from the hanging wall near the Mojado thrust trace (Zeller, 1970) indicates thrust displacement and resulting erosion of the Mojado Formation prior to Ringbone deposition. Displacement along the Ringbone fault was of sufficient magnitude to exhume ~1200 m of Mojado Formation.

**Big Hatchet Mountains**

The Big Hatchet Mountains contain a nearly complete section of lower and upper Paleozoic strata that generally strike northwest-southeast and dip southwest (Zeller, 1965). The oldest strata are in the north-northeast part of the range where lower Paleozoic strata overlie Proterozoic rocks on a nonconformity (Fig. 5). The most striking geologic formation in the Big Hatchet Mountains is the Pennsylvanian Horquilla Limestone, which defines many of the highest promontories and peaks in the range, including Big Hatchet Peak at 2550 m (Drewes, 1991). The structural geology comprises northwest-southeast–striking reverse and thrust faults that generally verge southwest, and a younger set of northwest-southeast–trending normal faults. The two most prominent reverse faults include the Mine Canyon and Big Tank faults (Fig. 5). The Mine Canyon fault is a complex southwest-verging fault zone of imbricate horse blocks that duplicate the Horquilla Formation and overlying Permian strata. The Big Tank fault, interpreted as a reverse fault by Zeller (1965), emplaces lower Permian rocks, in the northern hanging wall, over folded Bisbee Group strata (Drewes, 1991). The Bisbee Group consists of a stratigraphic succession similar to that observed in the Little Hatchet Mountains (Fig. 8) except that Jurassic strata are absent from the range; instead, lower Cretaceous rocks directly overlie Permian strata (Zeller, 1965; Drewes, 1991).

Northwest-southeast normal faults are present throughout the range. The age of these normal faults is inferred to be equivalent to northwest-trending faults and dikes in the Little Hatchet Mountains (Fig. 5). This inference is based on similar fault orientations and juxtaposition relations. Paleogene volcanic rocks in the southeastern Big Hatchet Mountains occupy the hanging walls of the northwest-southeast normal faults and are correlative to ignimbrites exposed in the central domain of the Little Hatchet Mountains (McIntosh and Bryan, 2000).

### CONTRASTING STRUCTURAL LEVELS AND RELATIONS

Structural relations in the Hatchet ranges provide key evidence for pre-Laramide and post-Laramide fault evolution and kinematics. The regional cross section (Fig. 7A) demonstrates that the Hatchet ranges expose four recognizable structural levels, which include, from deepest to shallowest: (1) a deep structural level consisting of Precambrian rocks exposed between the Granite Pass–Windmill fault system and the Hatchet Gap fault; (2) an intermediate level of southwest-dipping Paleozoic rocks in the Big Hatchet Mountains north of the Big Tank fault; (3) a shallower level that consists of southwest-dipping Bisbee Group strata in the central structural domain of the Little Hatchet Mountains and in the footwall of the Big Tank fault in the Big Hatchet Mountains; and (4) a shallow level where Laramide syntectonic strata and ignimbrites are exposed in the northern domain of the Little Hatchet Mountains (Fig. 7B) and in down-dropped fault blocks along east-west and northwest-southeast normal faults.

The deepest structural level between the Granite Pass and Hatchet Gap faults (Figs. 5 and 10) exposes Grenville-age (ca. 1.1 Ga) igneous rocks and a nonconformable contact with overlying Cambrian Bliss Sandstone. The approximately southwest-dipping Paleozoic section of the Big Hatchet Mountains nonconformably overlies Precambrian rocks and generally defines the backlimb of the northeast-vergent Hidalgo uplift (Fig. 7A). The Hidalgo uplift is bounded to the south by the Mine Canyon and Big Tank faults. These southwest-vergent reverse faults are of lesser total displacement than the combined Granite Pass and Windmill faults and thus are considered as secondary structures to the main northeast-vergent reverse faults, which emplace Precambrian rocks over Paleozoic and lower Cretaceous rocks. The opposed vergence of the Mine Canyon–Big Tank and Granite Pass–Windmill fault systems created an asymmetric bivergent wedge with the Big Hatchet Mountains in the core of the uplift. This bivergent style is similar to Laramide basement-involved uplifts of the central Rocky Mountain region, where seismic reflection data and subsurface well control augment extensive field exposures for detailed cross-section construction (e.g., southern Beartooth Mountains; Neely and Erslev, 2009).

Paleozoic strata are inferred to underlie the Little Hatchet Mountains, as indicated by thin slivers of Paleozoic rocks near Granite Pass and local exposures beneath Jurassic strata near the Copper Dick fault (Figs. 5 and 10; Zeller, 1970; Lawton and Harrigan, 1998). Although of uncertain thickness and extent, the Paleozoic strata regionally thin northward away from the axis of the Paleozen Pedregosa basin, now largely inverted in the Big Hatchet Mountains (Thompson et al., 1978).

The central domain of the Little Hatchet Mountains, between the Windmill and Copper Dick faults, represents the southernmost footwall block of the Hidalgo uplift that underlies the Late Cretaceous Laramide unconformity. In turn, the Copper Dick fault juxtaposes a full section of pre-Laramide Mesozoic strata in the structurally higher southern footwall block (central domain) against Laramide synorogenic strata of the Ringbone basin and overlying Paleogene ignimbrite strata only preserved in the hanging wall (northern do-
main). We infer that the central and northern domains of the Little Hatchet Mountains are two structural levels within the footwall of the Hidalgo uplift.

Recognition of the north-south–trending Livermore Spring normal fault requires a reinterpretation of the Copper Dick fault. The two segments of the Copper Dick fault were previously interpreted as parts of a steep, continuous Laramide right-lateral strike-slip fault that passed through an abrupt left-step restraining bend (Zeller, 1970; Hodgson, 2000) at what is interpreted here as the Livermore Spring fault. The former interpretation derived from apparent emplacement of the U-Bar Formation over the Ringbone Formation at the fault bend. Structural relations demonstrate normal displacement on the Copper Dick fault, and sheared upper Eocene–Oligocene granite was likely intruded along the fault zone during active fault dilation. Mylonitic U-Bar limestone in the fault zone likely formed in the presence of recrystallization temperatures between 300 and 400 °C (e.g., Bernabe and Brace, 1990). We infer that the Paleogene granite intrusions, mylonitic marble blocks, and north-south elongated limestone pebbles in the Broken Jug Formation indicate high geothermal gradients during north-south extension, which took place during latest Eocene–Oligocene time on the basis of the ages of the granite intrusion (Fig. 9D) and rhyolite dikes elsewhere in the range (Table 1). Extension was thus synmagmatic and of sufficient magnitude to generate normal faults, some with throws exceeding 3000 m (e.g., Copper Dick fault). Moreover, overlapping ages of the Oligocene silicic igneous rocks in the range, including the 34 ± 1 Ma granite intrusion along the Copper Dick fault, a 33 Ma ignimbrite associated with the thick volcaniclastic section in the Bull Canyon graben, and the 32–27 Ma rhyolite dikes, indicate likely synextensional deposition of Oligocene volcanic rocks.

Neogene displacement on the Livermore Spring fault served to expose variable structural depths of intrabasinal Laramide thrust faults. The U-Bar Formation in the hanging wall of the Mojado thrust system, whereas preserved west of the Livermore Spring fault, is now eroded east of the fault, where only the subthrust Ringbone Formation is exposed (Fig. 11). Extension was thus synmagmatic and of sufficient magnitude to generate normal faults, some with throws exceeding 3000 m (e.g., Copper Dick fault). Moreover, overlapping ages of the Oligocene silicic igneous rocks in the range, including the 34 ± 1 Ma granite intrusion along the Copper Dick fault, a 33 Ma ignimbrite associated with the thick volcaniclastic section in the Bull Canyon graben, and the 32–27 Ma rhyolite dikes, indicate likely synextensional deposition of Oligocene volcanic rocks.

Extensive exposures of the Hidalgo Formation (Young et al., 2000) occur north of the Hidalgo fault. The Hidalgo Formation is age correlative with the upper member of the Ringbone Formation and the Skunk Ranch Formation (Clinkscales and Lawton, 2014). The thick section of Hidalgo Formation, which is mostly restricted to north of the Hidalgo fault, suggests that this fault may have served as an intrabasinal partitioning structure within the Laramide Ringbone basin.

Figure 11. Conceptual sketch drawing for older-on-younger juxtaposition across the north-south Livermore Spring fault. Cross-sectional line is shown in Figure 10. (A) Structure before offset along the Livermore Spring fault. The Mojado and Skunk Ranch faults define thrust sheets with U-Bar Formation in the hanging wall overriding Ringbone Formation. (B) Thrust sheets with U-Bar Formation in thrust hanging-wall blocks are offset by the Livermore Spring fault. This resulted in older-on-younger juxtaposition of structurally higher thrust sheets emplaced against lower plate Ringbone Formation.
**DISCUSSION**

Pre-Laramide Structure and Basin Configuration

Correlation of Bisbee Group strata and lower Cretaceous subcrop relations reveal the rift geometry of the Bisbee basin in southern New Mexico (Fig. 4). Bisbee Group strata crop out in nearby ranges, including the Animas, Burro, Chiricahua, and Peloncillo Mountains, and the Cookes Range (Fig. 3). In the Little Hatchet Mountains, a thick Bisbee Group section, the thickest in the region, includes the upper Jurassic Broken Jug Formation (1228 m), a thick U-Bar section (~970 m versus ~240 m north of Copper Dick fault), and thick Mojado Formation (~1200 m). The upper Jurassic to lower Cretaceous Bisbee Group thins from a thick former basin keel in the Little Hatchet Mountains (Lucas and Lawton, 2000; Lawton, 2004; Machin, 2013), north to the Burro Mountains and Cookes Range to an area of less accommodation on the margin of the basin. Upper Cretaceous strata equivalent to the upper part of the Mojado Formation in the Burro Mountains unconformably overlie Precambrian rocks (Mack et al., 1986; Lawton, 2004; Machin, 2013).

The thinning of upper Jurassic to upper Cretaceous strata north of the Little Hatchet Mountains can be attributed to the fault block geometry of the Bisbee basin and proximity to the rift shoulder of the Mogollon Highlands (Fig. 1). In addition, a similar north-northeast thinning trend for lower-upper Cretaceous rocks can be attributed to the geometry of a post-rift early Late Cretaceous foreland basin (Mack, 1987; Clinkscales and Lawton, 2014). The transition to a foreland basin setting is represented by the thick (>1200 m) Mojado Formation and Cenomanian marine, ammonite-bearing facies of the Mancos Formation (Lucas and Lawton, 2000, 2005), deposited in a basin foredeep situated in the Little Hatchet Mountains, and thinner correlative Beartooth Formation in the Burro Mountains deposited in a forebulge or distal foredeep position (Mack, 1987; Machin, 2013).

Laramide Clastics, Volcanism, and Uplift Style

Contemporary arc volcanism is recorded in the Laramide syntectonic rocks of the Little Hatchet Mountains. Ash-fall tuffs and basaltic andesite are interbedded with continental syntectonic deposits (Basabilvazo, 2000; Jennings et al., 2013), and the thick (>1700 m) ca. 70 Ma Hidalgo Formation, consisting dominantly of basaltic andesite flows (Young et al., 2000). The syntectonic Laramide section was deposited between ca. 75 and 70 Ma (Clinkscales and Lawton, 2014), and emplacement of the Sylvanite plutonic complex ca. 69 Ma appears to postdate, or coincide with, the waning stages of Laramide deposition in the Ringbone basin. The intrusion is also likely postdepositional based on comparison of intruded strata in the footwall of the Copper Dick fault and synorogenic conglomerate clasts of the Ringbone and Skunk Ranch Formations. Strata near the Sylvanite complex are pervasively thermally metamorphosed and all Bisbee strata in the central domain show some evidence of thermal alteration, whereas clasts in conglomerate of the Ringbone and Skunk Ranch Formations are not metamorphosed. These clasts were dominantly derived from the eroded core of the Hidalgo uplift in the Big Hatchet Mountains with possible minor contribution from the southern domain of Little Hatchet Mountains. However, the absence of thermal alteration of source rocks prior to synorogenic clast production indicates that the Sylvanite intrusive complex, only ~1 m.y. younger than uppermost preserved Laramide strata, immediately postdated Ringbone and Skunk Ranch deposition. This observation, along with the thick basaltic andesite flows assigned to the Hidalgo Formation, indicates that by the earliest Maastrichtian, the Ringbone basin was converted from a subsiding depocenter dominated by alluvial, fluviual, and lacustrine sedimentation to a volcanic center. No evidence of early Paleogene deformation or associated syntectonic clastic deposition is recognized in southwesternmost New Mexico. However, Paleogene clastic strata are documented elsewhere in the region, notably the northern Florida and Victoriо Mountains (Lobo Formation; De los Santos et al., 2016) and along the Rio Grande rift near Las Cruces, New Mexico (Love Ranch Formation; Seager et al., 1997).

The dimensions, orientations, and extents of the southern Cordilleran Laramide structures and basins are a result of the antecedent structural architecture of the Border rift. The geographic extent of Laramide uplifts and basins in southwestern New Mexico is projected from exposed reverse and thrust structures, comparison of stratigraphic sections across ranges, and sparse well control (Hodgson, 2000; Seager, 2004). Despite the relative position of the Tarahumara arc to the Hidalgo uplift and Ringbone basin, the foreland of southern New Mexico did not develop into a thin-skinned retroarc thrust-system. We infer that if the preexisting Bisbee rift structures had not been present, the region may have been more akin to other retroarc thin-skinned provinces (e.g., Sevier thrust belt), but the presence of preexisting, basement-involved normal faults facilitated fault reactivation and uplift of granitic Mesoproterozoic basement blocks and the development of bivergent block uplifts (Fig. 12). In addition, the Laramide uplifts in southern New Mexico have a shorter uplift-to-basin wavelength than contemporaneous structures in the central Rocky Mountain region and are of lesser areal extent. As a simple comparison, the Bighorn Mountains of Montana and Wyoming are ~55 km wide in the northeast-southwest direction and flanked by the ~100-km-wide Bighorn basin. In contrast, the width of the Hidalgo uplift, projected between its flanking reverse faults in the northeast-southwest direction, is ~20 km and the maximum width of the Ringbone basin is ~40 km (approximate distance between Granite Pass fault and Luna uplift; Fig. 3). Furthermore, the current areal extent of the Hidalgo uplift and Ringbone basin is a maximum width if post-Laramide extension is considered (Fig. 12).

The occurrence of synorogenic volcanic rocks, the coeval Tarahumara arc in Sonora, Mexico, and nearby magmatism (Fig. 3) are major factors that differentiate the Laramide orogen in southern New Mexico from contemporaneous uplifts in the central Rocky Mountains. Late Cretaceous (Campanian) Laramide shortening in southern New Mexico encompassed an area from the Hidalgo uplift to the Rio Grande uplift with active local magmatism from ca. 76 to 69 Ma (Amato et al., 2017; this study). By the end of the Campanian (ca. 69 Ma), the Ringbone basin in the Little Hatchet Mountain area no longer a subsiding depocenter accumulating continental clastics, but a transformed volcanic center.
The Broken Jug Formation (Jb) does not crop out in the Big Hatchet Mountains and the thickest known exposures occur south of the Copper Dick fault. The northern limit of the Jb is unknown; however, the section likely thins northward onto higher former rift blocks.

The thickness and continuity of the Paleozoic section are unknown. Depth to Mesoproterozoic basement unknown.

Figure 12. Structural restoration of the Little and Big Hatchet Mountains with preserved formation thicknesses and line length. Formation labels as in Figures 5 and 10 (v.e.—vertical exaggeration). (A) Present-day structure with dip tadpoles and projected contacts based on field relations. Line of section is identical to Figure 7A and location is shown as A-A’ in Figure 5. (B) Paleogene extension and magmatism restored. Fault offset on the Big Tank and Mojado faults is restored to simplify section. Section illustrates the asymmetry of the biergent Hidalgo uplift. The Laramide unconformity represents a conceptual erosional base over the main uplift that existed during Laramide shortening. This line of section does not intersect Laramide synorogenic strata directly north of the Copper Dick fault; however, Laramide synorogenic rocks are only preserved in the northern hanging wall. (C) Schematic pre-Laramide line length restoration. Line lengths for Mojado and U-Bar Formations were preserved across the cross section and indicate ~8 km of shortening. Limited Paleozoic exposures in the Little Hatchet Mountains do not permit robust inferences regarding the stratigraphic thickness of the Paleozoic section and the nature of the Paleozoic and Mesozoic contact north of the Granite Pass–Windmill fault system; therefore, the Paleozoic section is not restored in detail. The Broken Jug Formation (Jb) does not drop out in the Big Hatchet Mountains and the thickest known exposures occur south of the Copper Dick fault. The northern limit of the Jb is unknown; however, the section likely thins northward onto higher former rift blocks.
Late Cretaceous magmatism in southern New Mexico has been attributed to a migrating volcanic arc that attended the progressive shallowing of the Farallon plate (McMillan, 2004); nevertheless, when assessed in detail, the distribution and age of Late Cretaceous plutons in southern New Mexico suggest no systematic younging trend to the northeast or batholith parallel to the trench. For example, the Copper Flat porphyry system in the Animas Hills (Fig. 3) has a ca. 75 Ma age (McLemore et al., 2000), but is located northeast of the younger 70-69 Ma volcanic centers for the Hidalgo Formation and Sylvanite plutonic complex in the Little Hatchet Mountains and Late Cretaceous copper porphyry systems in southeastern Arizona (e.g., Lang and Titley, 1998).

In contrast, Cretaceous magmatism in central Sonora, Mexico, appears to follow an expected northeast younging trend with plutonic and volcanic rocks parallel to the trench (González-León et al., 2011). We suggest that Late Cretaceous magmatism in southern New Mexico and southeastern Arizona resulted from localized convection along the southeast margin of a subducting oceanic plateau (Liu et al., 2010), perhaps at a tear fault at the edge of the classic Late Cretaceous flat slab corridor (Fig. 1; e.g., Valencia-Moreno et al., 2017).

The resultant northeast-southwest magmatic belt along the flat slab margin would have been contemporaneous with trench-parallel arc volcanism in central Sonora, Mexico. However, by the Eocene the volcanic arc appears to have migrated northeast into southern New Mexico (McMillan, 2004), suggesting progressive shallowing of the Farallon plate in the Paleogene and attendant magmatic activity. Future investigations should consider Late Cretaceous magmatism in southern New Mexico in relation to the southeast margin of the Late Cretaceous Laramide flat slab corridor and concomitant Laramide structures and porphyry complexes in southeastern Arizona.

**Paleogene Extension and Magmatism**

In the Great Basin region of the western U.S., a southwestward sweep in arc magmatism occurred from ca. 50 Ma in Idaho and Montana, 40 Ma in central Nevada, and ca. 20 Ma in southern Nevada (Fig 2; Dickinson, 2002, 2013). Paleoelevation and paleoclimate models for the Great Basin region indicate that this southward sweep in Paleogene magmatism was coincident with a protracted migration in surface uplift and metamorphic core complex formation (e.g., Mix et al., 2011); however, the timing for development of high-elevation, rugged topography in the Great Basin region is still unresolved, as indicated by detailed mapping and geochronology that challenge the ages, stratigraphic positions, and implied significance of rock samples used in previous stable isotope studies (Lund Snee et al., 2016). The Cordillera of the southwestern U.S. and Sonora, Mexico, likewise underwent a diachronous west to southwest sweep in magmatism, extension, and surface uplift(?!) from southern New Mexico ca. 34 Ma (Coney and Reynolds, 1977; Dickinson, 2002; this study), through Arizona and Sonora, Mexico, from 30 to ca. 20 Ma (Dickinson, 2002, 2006). In southern Arizona and Sonora, the westward migration of magmatism coincides with the development of large-magnitude extensional fault systems (Gans, 1997) and metamorphic core complexes (Davis, 1980; Coney and Harms, 1984). Metamorphic core complexes similar to those in southern Arizona have not been identified in the Little and Big Hatchet Mountains, but the east-west normal faults may represent an earliest embryonic core complex (e.g., Rick- etts et al., 2015) or the structurally highest fault segment of a metamorphic complex. However, low-angle normal faults, with similar northwest-southeast orientations, are present at Mahoney Ridge in the Florida Mountains (Fig. 3), which were mapped as low-angle thrust faults with younger-on-older separation (Brown and Clemons, 1983).

Models explaining latest Eocene–Oligocene extension in southwest New Mexico must take into account the large-volume silicic volcanism and magmatism of the period, recorded by the local Boot Heel (e.g., Mcintosh and Bryan, 2000) and Mogollon-Datil volcanic fields (Mcintosh et al., 1992). Magmatism and extension occurred in pulses (Mcintosh and Bryan, 2000), as indicated by ca. 34 Ma intrusions along the Copper Dick fault and Granite Pass pluton, and ca. 27 Ma latite dikes (Cleary, 2004). These intrusions are age correlative to ignimbrite rocks ubiquitous throughout the region (Fig. 3). Although an unequivocal relationship between east-west and northwest-southeast normal faults and expanded growth ignimbrite sections in hanging-wall blocks cannot be firmly established in the Little and Big Hatchet Mountains, the occurrence and preservation of the thickest ignimbrite exposures in the hanging walls suggest a synkinematic association.

On the basis of thick tilted sections of Oligocene ignimbrites near Silver City, New Mexico (Fig. 3), some workers have inferred that Laramide shortening continued as late as the Oligocene (Copeland et al., 2011; Tomlinson et al., 2013). Thickening of the ignimbrite section near Silver City is interpreted to have taken place on the hanging walls of blind thrust faults as part of growth monocline structures. In contrast, the thickest preserved sections of Eocene–Oligocene ignimbrite rocks in the Hatchet ranges are located within grabens associated with unambiguous normal faults, where the ignimbrites depository-truncate Laramide thrust faults and unformably overlie Laramide syntectonic strata. Shortening-related growth in the ignimbrite section near Silver City may reveal local strain complexities contemporaneous with extension in the Hatchet ranges; nevertheless, our analysis contravenes a shortening origin for the ignimbrite growth monoclines. We speculate that these tilted Oligocene sections are of extensional origin, as tilted footwall blocks or monoclines cored by blind normal faults, based on late Eocene–Oligocene subregional to regional deformation trends (Fig. 2) and the similar age and orientation for northwest-southeast and east-west surface-breaking normal faults in the Little Hatchet Mountains. No field evidence in the Hatchet ranges or other nearby ranges corroborates Oligocene shortening; instead, evidence indicates regional Oligocene extension.

Late Eocene–Oligocene extension and magmatism in the Hatchet ranges likely resulted from a combination of factors ultimately associated with changing plate interactions between the Farallon and North American plates (e.g., Coney and Harms, 1984; Engebretson et al., 1984). Extension in the region is part of a regional trend of backarc extension that took place as the Farallon plate foundered westward (Humphreys, 1995; Dickinson, 2002), accompanied...
by asthenospheric flow into the mantle wedge during plate retreat. Upwell-
ing asthenosphere led to the voluminous silicic magmatism of the Boot Heel (e.g., McIntosh and Bryan, 2000) and Mogollon-Datil volcanic fields (McIntosh et al., 1992). Extension that accompanied latest Eocene–Oligocene magmatism may have been induced by crustal weakening caused by renewed magmatism associated with the rollback of the Farallon plate, and gravitational instability of the upper crust as a response to crustal thickening accompanying heat ad-
vection (e.g., Liu, 2001) and/or magmatic additions to the crust. Furthermore, it is likely that variations in normal fault orientations from east-west to north-
west-southeast could have been controlled by local perturbations around vol-
canic centers (e.g., Nieto-Samaniego et al., 1999) and/or slight strain rotation related to different pulses of magmatism.

On the basis of the close temporal relationship between Paleogene silicic magmatism and north-south extension in southwestern New Mexico, pre-
Basin and Range extension was evidently not associated with simple gravi-
tational instability in a high-elevation hinterland plateau as suggested for the Sevier hinterland, or Nevadaplano (Fig. 1; e.g., Druschke et al., 2011). We con-
clude that extension was not a result of gravitational collapse of a high-stand-
ing Laramide region because the onset of Paleogene magmatism and exten-
sion ca. 34 Ma took place –18 m.y. after the youngest record of syn-Laramide deposition in the region ca. 52 Ma, corresponding to the uppermost inferred age of the Lobo Formation (De los Santos et al., 2016). This does not preclude crustal thickening as an important mechanism leading to extension; however, crustal thickening and eventual instability were likely associated with cumula-
tive thickening that resulted from Late Cretaceous shortening and magmatism, and culminated in magmatic additions to, and thermal weakening of, the crust during the Paleogene.

**CONCLUSIONS**

Four generations of Jurassic through Oligocene structures in the Hatchet ranges of southwesternmost New Mexico provide a template for the Mesozoic to Paleogene kinematic evolution of those ranges and regional crustal evolu-
tion of the southern U.S. Cordillera. Laramide uplifts and basins of southern New Mexico were the result of basement-involved deformation in the pres-
ence of active plutonic centers. Late Cretaceous magmatism in southern New Mexico may have been the result of convection along the southeast margin of a subducting oceanic plateau contemporaneous with arc volcanism in cen-
tral Sonora, Mexico. Local volcanism and smaller uplift-to-basin wavelengths distinguish the southern U.S. Cordillera from coeval Laramide structures in the central Rocky Mountains. The narrow uplift-to-basin configuration is a consequence of the distribution of Jurassic–Early Cretaceous normal faults of the Border rift. The existence of pre-Laramide normal faults is recorded by local thickness variations of upper Jurassic to lower Cretaceous strata as well as regional northward thinning of Mesozoic strata and abrupt changes in lower Cretaceous subcrop. An inverted graben within the Bisbee basin, de-
finied by bivergent thrust and reverse faults, is exposed in southwesternmost New Mexico. This interpretation is in stark contrast to proposed thin-skinned deformation throughout the southern U.S. Cordilleran region (e.g., Corbit and Woodward, 1973; Drewes, 1988). However, thin-skinned deformation in southern Arizona (e.g., thrust structures in the San Pedro trough area; Dick-
inson, 1991) may have been contemporaneous to the Laramide structures in the Hatchet Mountains, and future studies can resolve the spatial distribu-
tion of these disparate structural styles. Regional shortening ended by early Eocene time (ca. 52 Ma), as indicated by local structural relations and basin
development in southern New Mexico. Late Cretaceous faults and folds are displaced by latest Eocene to Oligocene east-west– and northwest-southeast-
trending dikes and normal faults, with some normal fault throws exceeding 3000 m. Late Eocene–Oligocene extension was synmagmatic, as indicated by (1) east-west–trending rhyolite dikes, some intruded along normal faults, (2) sheared Oligocene granite intrusions along the Copper Dick normal fault, and (3) thick contemporary ignimbrite sections in Eocene–Oligocene grabens. Eocene–Oligocene arc magmatism is attributed to asthenospheric upwell-
ning and crustal melting as the Farallon plate foundered westward, following the shallower slab subduction phase of the Laramide orogeny. A west to south-
west migration of the Paleogene magmatic front led to thermal weakening, extension, and possibly surface uplift, that continued from southwestern New Mexico (ca. 34 Ma) to the metamorphic core complexes of Sonora, Mexico, and Arizona. This west and southwest migration of arc magmatism was cont-
emporaneous with a southwest sweep in magmatism in the Great Basin re-
gion. Future integrative tectonic studies on the southern U.S. Cordillera could address crustal thickness and attendant paleoaltimetric changes from the Late Cretaceous and Paleogene. Ultimately, these studies, linked to the Great Basin region, would shed light on the climatic and surface evolution of the greater Western Cordillera prior to the development of the San Andreas fault system and opening of the Basin and Range and Rio Grande rift.

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**REFERENCES CITED**


Amato, J.M., Mack, G.H., Jonell, T.N., Seager, W.R., and Upchurch, G.R., 2017, Onset of the Laramide orogeny and associated magmatism in southern New Mexico based on U-Pb geochro-


