New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/69



U-Pb geochronology of middle–late Eocene intermediate volcanic rocks of the Palm Park Formation and Orejon Andesite in south-central New Mexico

R.H. Creitz, B.A. Hampton, G.H. Mack, and J.M. Amato
2018, pp. 147-157. https://doi.org/10.56577/FFC-69.147
Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2018004

in:
Las Cruces Country III, Mack, Greg H.; Hampton, Brian A.; Ramos, Frank C.; Witcher, James C.; Ulmer-Scholle, Dana S., New Mexico Geological Society 69th Annual Fall Field Conference Guidebook, 218 p.
https://doi.org/10.56577/FFC-69

This is one of many related papers that were included in the 2018 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 69th Field Conference, Las Cruces Country III, 2018, p. 147-157.

U-PB GEOCHRONOLOGY OF MIDDLE–LATE EOCENE INTERMEDIATE VOLCANIC ROCKS OF THE PALM PARK FORMATION AND OREJON ANDESITE IN SOUTH-CENTRAL NEW MEXICO

Ryan H. Creitz, Brian A. Hampton, Greg H. Mack, and Jeffrey M. Amato

Department of Geological Sciences, New Mexico State University, Las Cruces, NM 88003, USA; bhampton@nmsu.edu

Abstract—U-Pb zircon ages from the middle–late Eocene intermediate volcanic rocks of the Palm Park Formation and Orejon Andesite provide new geochronologic constraint on the duration of volcanism that took place just after the Laramide orogeny and prior to the onset of latest Eocene bimodal volcanism and initiation of the Rio Grande rift in south-central New Mexico at ~36 Ma. Presented here are nine new U-Pb zircon ages (n=247 analyses) from the Organ, Doña Ana, Robledo, and Sierra de las Uvas Mountains that fall within a range of ~45–40 Ma. The oldest age determined from this study was collected from an ash-fall tuff exposed in the lower part of the Palm Park Formation in the Robledo Mountains (Apache canyon) and yields an age of 45.0±0.7 Ma. Three samples from intermediate volcanic flows in the Orejon Andesite of the Organ Mountains (Fillmore canyon) yield ages of 44.0±1.5, 43.8±0.4, and 42.8±1.5 Ma. Four samples were collected from a series of intermediate composition (andesite to dacite) volcanic flows in the Doña Ana Mountains (Cleofas canyon) and Robledo Mountains (Faulkner canyon) and yield ages of 41.6±0.7, 41.3±0.7, and two nearly-identical ages of 41.0±0.6 Ma. The youngest age reported from this study was determined from an ash-fall tuff exposed near the top of the Palm Park Formation in the eastern part of the Sierra de las Uvas fault block and yields an age of 39.6±0.5 Ma. New data are presented here, together with previously reported ages and fossil occurrences from the Palm Park Formation, Orejon Andesite, and equivalent units throughout south-central New Mexico, including the Cleofas Andesite and Rubio Peak Formation. Based on new ages and fossil age ranges, we favor a model where these rocks were erupted and deposited over a ~10 my period between ~46–36 Ma during which mantle wedge material was re-introduced throughout south-central New Mexico just prior to onset of the Rio Grande rift.

INTRODUCTION

The Late Cretaceous–middle Eocene Laramide orogeny was the final stage of mountain building associated with ocean-continent convergence and subduction of the Farallon plate beneath western North America and marks the tectonic transition from a more steeply-dipping subducting slab and thin-skinned deformation of the Sevier orogeny to more shallowly-dipping subduction and thick-skinned, basement-involved deformation (e.g., Dickinson and Snyder, 1978; Seager, 1981; Seager et al., 1986; Dickinson et al., 1988, Seager et al., 1997; DeCelles, 2004; Dickinson, 2004; Nummendal, 2004; Seager, 2004). Throughout the southwestern U.S., this tectonic transition resulted in the eastward, inboard stepping of the Cordilleran orogenic front, foreland depocenters, and magmatic-volcanic centers into parts of eastern Arizona and central New Mexico (e.g., Snyder et al., 1976; Dickinson and Snyder, 1978; Seager, 2004; McMillan, 2004; Amato et al., 2017). The final Paleocene–middle Eocene deformational stage of the Laramide orogeny in southernmost New Mexico has been well documented (Figs. 1, 2) and is recorded by nonmarine clastic strata that are preserved in a series of short-wavelength, wedge-top basins that include the Little Hat Top, Skunk Ranch, Klondike, Potrillo, and Love Ranch basin (Fig. 2; Seager et al., 1986; Seager and Mack, 1986; Mack and Clemons, 1988; Lawton and Clemons, 1992; Lawton et al, 1993; Seager et al, 1997; Seager, 2004; Clinkscales and Lawton, 2014). Although there is a near-continuous stratigraphic record of Paleocene–middle Eocene synorogenic sedimentation throughout south-central New Mexico, little is known about the age and duration of middle–late Eocene magmatism, volcanism, and volcaniclastic sedimentation that occurred just after Laramide deformation and prior to the onset of latest Eocene–Oligocene bimodal volcanism of the "ignimbrite flare-up" and initiation of the Rio Grande rift in this region at ~36 Ma (Fig. 3; e.g., Cather et al., 1984; Cather, 1990; McIntosh et al., 1992 Mack et al., 1998; Lawton and McMillan, 1999; McMillan et al., 2000). At the largest scale, it is also unclear what lithosphere-scale mechanisms were driving mid–late Eocene magmatism just prior to the onset of the Rio Grande rift.

The focus of this study is on age relationships of intermediate volcanic and volcaniclastic strata of the middle–late Eocene Palm Park Formation and Orejon Andesite that crop out throughout south-central New Mexico (Figs. 1, 3). Presented here are nine new U-Pb zircon ages from ash-fall tuffs and intermediate volcanic flows that crop out in the Organ, Doña Ana, Robledo, and Sierra de las Uvas Mountains near Las Cruces, New Mexico (Fig. 1). New ages from these rocks help constrain the initial onset, overall duration, and final termination of post-Laramide, pre-rift volcanism in south-central New Mexico. Results from this study are presented and discussed in the context of age-equivalent, pre-rift volcanic and volcaniclastic strata that are exposed in other parts of south-central New Mexico (e.g., Caballo, Potrillo, Goodsight, southern San Andres Mountains, Black Range and Cooke's Range; Fig. 1).

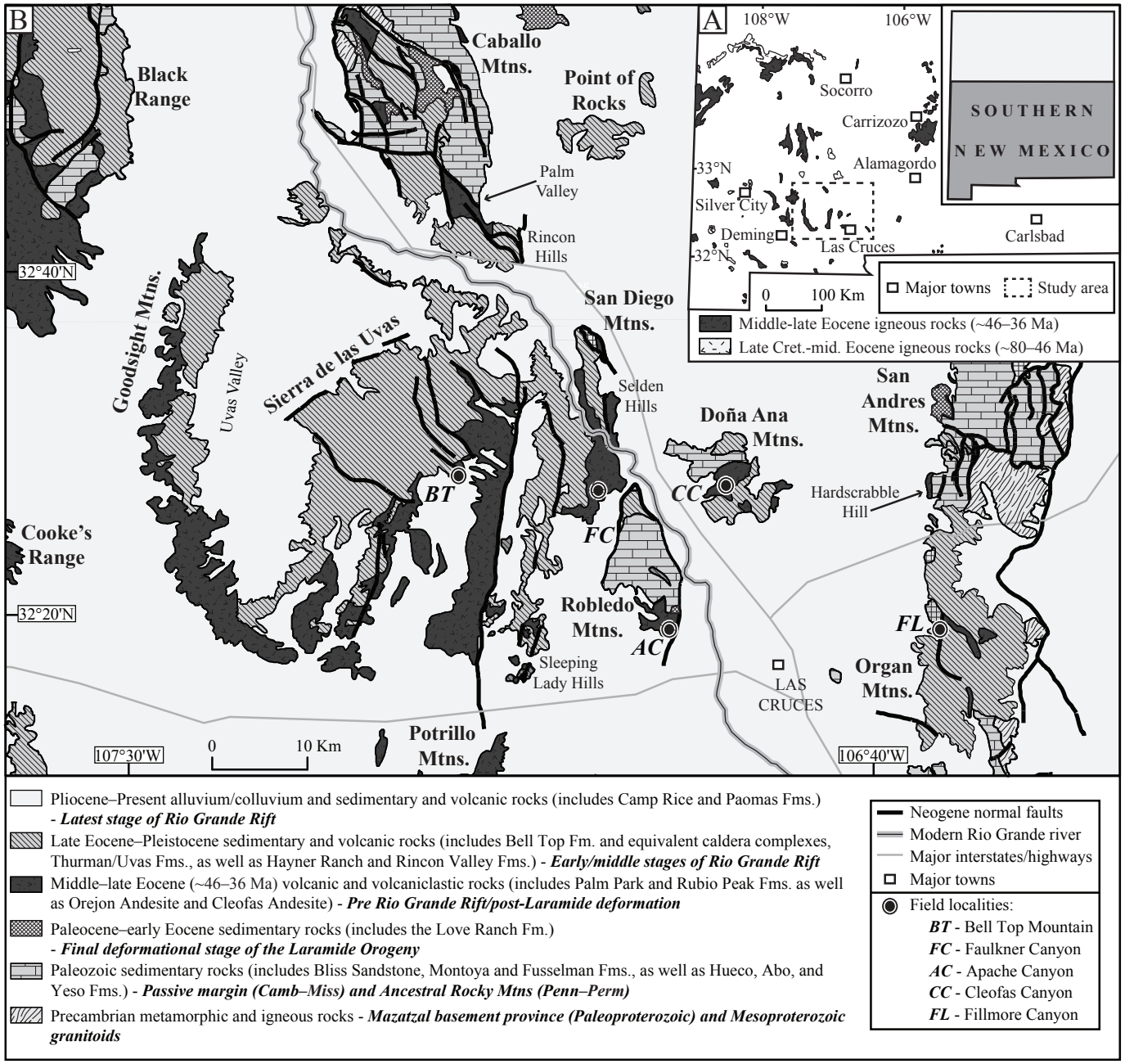


FIGURE 1. Generalized geologic map of south-central New Mexico with emphasis on middle–late Eocene volcanic and volcaniclastic rocks of the Palm Park Formation, Orejon Andesite, Rubio Peak Formation, and Cleofas Andesite. Geologic and geographic data from New Mexico Bureau of Geology MR, 2003 data base NMBGMR, 2003.

STRATIGRAPHIC AND GEOCHRONOLOGIC OVERVIEW

The tectonic transition from the final deformational stage of Laramide orogenesis to the initiation of the Rio Grande rift in south-central New Mexico is recorded by a near-continuous stratigraphic record that includes from-base-to-top (1) Paleocene–earliest middle Eocene synorogenic strata of the Love Ranch Formation, (2) middle Eocene–earliest late Eocene volcanogenic and volcaniclastic strata of the Palm Park Formation and Orejon Andesite (and roughly age-equivalent rocks of the Rubio Peak Formation and Cleofas Andesite; Table 1), and (3) latest Eocene–early Oligocene volcanic rocks of the Bell Top Formation (and associated ignimbrite rocks of the Doña Ana and Organ caldera complexes; Fig. 3; e.g., Seager 2004). The Love Ranch Formation represents the final stage of deformation and sedimentation associated with the Laramide orogeny (Seager, 2005). The lower age range for the Love Ranch is constrained biostratigraphically by late Paleocene–early Eocene palynomorphs in the basal parts of the unit (Thompson, 1982; Seager et al., 1997). The contact between the upper parts of the Love Ranch and overlying rocks of the Palm Park Formation (and equivalent units) can be observed in localized Laramide paleovalleys where the Love Ranch appears to conformably

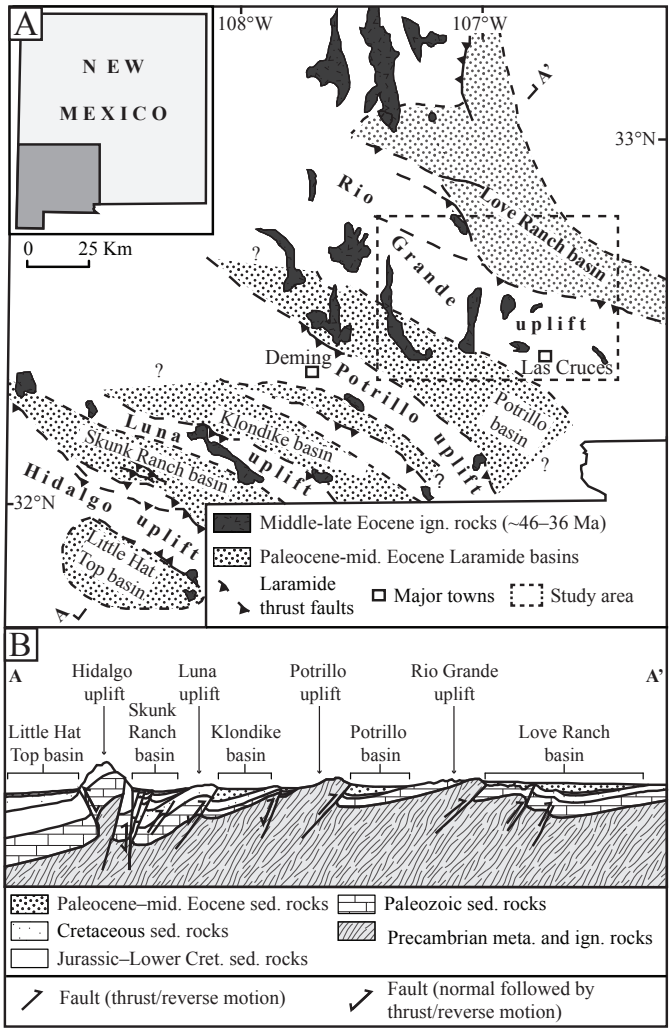


FIGURE 2. **A**) Tectonostratigraphic map of Paleocene–middle Eocene Laramide uplifts and adjacent wedge-top basins and middle–late Eocene igneous rocks of the Palm Park Formation, Orejon Andesite, Rubio Peak Formation, and Cleofas Andesite in south-central and southwesternmost New Mexico. Dashed rectangle denotes location of study area in south-central New Mexico (from Fig. 1). **B**) Generalize geologic cross-section of Laramide uplifts and basins that corresponds with section line A-A'. Modified from Seager (2004).

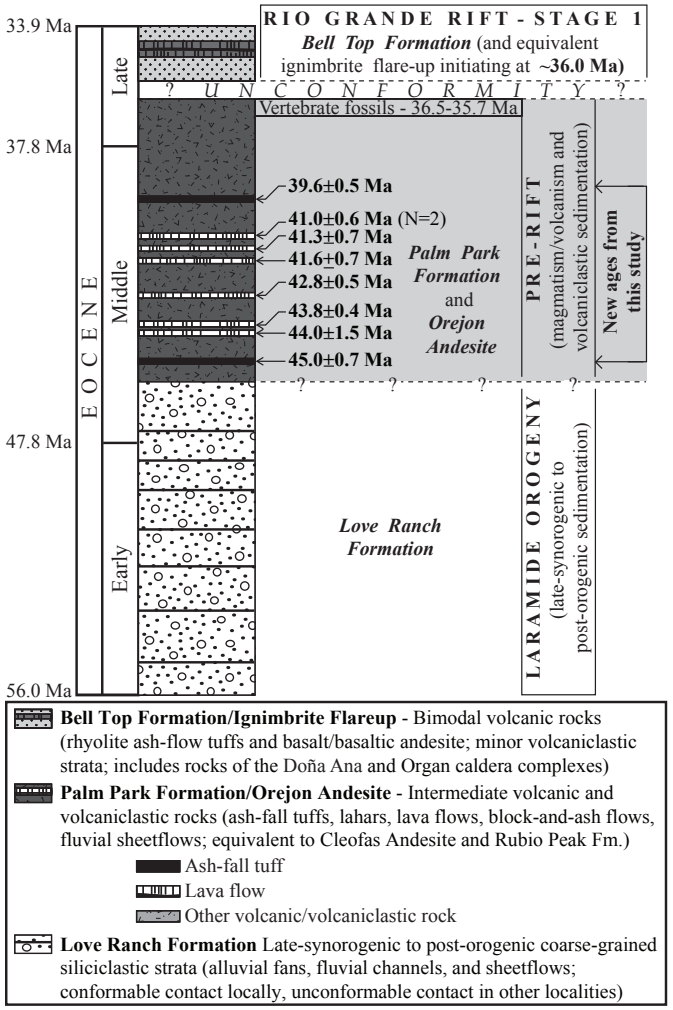


FIGURE 3. Generalized stratigraphic overview of early–late Eocene rocks in south-central New Mexico including late-synorogenic to post-orogenic strata of the Love Ranch Formation (Laramide orogeny), pre-rift volcanic and volcaniclastic rocks of the Palm Park Formation and Orejon Andesite (focus of this study), and late Eocene volcanic and volcaniclastic rocks of the Bell Top Formation and age-equivalent rocks of the Doña Ana and Organ caldera complexes (i.e., ignimbrite flare-up). Stratigraphic horizons with ages denote nine discrete sample localities with new U-Pb zircon ages reported in this study. Note that two samples with nearly identical ages (41.0±0.6 Ma) occupy the same stratigraphic horizon on this figure but represent two distinct sample localities. Vertebrate fossil age range is from Lucas and Williamson (1993), Lucas et al. (1997), and Lucas (2015).

underlie (and in some localities is interbedded with) the Palm Park Formation (Seager, 1981; Postma, 1986; Mack et al., 1994; Seager et al., 1997; Seager, 2004; Amato et al., 2017).

The onset of the Rio Grande rift in south-central New Mexico is marked by late Eocene (~36 Ma) bimodal volcanism and minor sedimentation recorded in members of the Bell Top Formation and rocks of the Organ caldera (e.g., Cueva, Achenback Park, Squaw Mountain Tuffs) and the Doña Ana caldera (e.g., Doña Ana Rhyolite and Goat Mountain Rhyolite; Fig. 3; Clemons, 1975; Seager et al., 1976; Seager, 1981; McIntosh et al., 1991; Mack et al., 1998; McMillan et al., 2000; Zimmerer and McIntosh, 2013). The late Eocene–early Oligocene age of the Bell Top Formation is based on $^{40}Ar/^{39}Ar$ dates from ash-flow tuff units that range from 35.7–28.6 Ma (McIntosh et al., 1991). The Cueva, Achenback Park, and Squaw Mountain have $^{40}Ar/^{39}Ar$ ages of 36.45±0.08, 36.23±0.14, and 36.0±0.16 Ma (Zimmerer and McIntosh, 2013), and U-Pb zircon ages of 36.441±0.020, 36.259±0.016, and 36.215±0.016 Ma (Rioux et al., 2016).

The contact between the top of the Palm Park Formation (and equivalent units) and base of the Bell Top Formation and age-equivalent ignimbrites of the Doña Ana and Organ calderas is poorly understood and may be an unconformable contact with little missing time (Fig. 3). Table 1 provides a summary of all published geochronologic ages from intermediate to mafic volcanic rocks that occupy the stratigraphic position of the Palm Park Formation and Orejon Andesite in south-central New Mexico. The following text provides a brief stratigraphic and geochronologic review of the middle–late Eocene rocks of the Palm Park Formation, Orejon Andesite, Cleofas

TABLE 1. Summary of all new and previously published geochronologic ages from intermediate to mafic volcanic rocks that occupy the stratigraphic position of the Palm Park Formation and Orejon Andesite in south-cental New Mexico.

Method	Age (Ma)	± (Ma)	Material Dated	Lithology	Formation	Reference
K-Ar	35.9	1.6	Plagioclase (I)	Andesite	Cleofas Andesite	Clemons, 1979
K-Ar	36.4	2.3	Hornblende (I)	Latite	Rubio Peak Fm.	Clemons, 1979
K-Ar	36.7	1.4	Hornblende (I)	Andesite porphyry	None listed	Loring & Loring, 1980
K-Ar	37.3	2.3	Hornblende (I)	Latite	Rubio Peak Fm.	Marvin and Cole, 1978
K-Ar	37.6	2.0	Hornblende (I)	Latite porphyry	Rubio Peak Fm.	Clemons, 1979
K-Ar	38.0	1.5	Biotite (I)	Dacite	Rubio Peak Fm. (?)	Clemons, 1982
K-Ar	38.1	2.0	Biotite (I)	Intermediate dike	Rubio Peak Fm. (?)	Clemons, 1979
U-Pb	***39.6**	***0.5**	Zircon (I)	Ash fall tuff	Palm Park Fm.	This study
Ar-Ar	40.2	0.25	Hornblende (I)	Andesite	Rubio Peak Fm.	McMillan, 2004
U-Pb	***41.0**	***0.6**	Zircon (I)	Intermediate porphyry	Palm Park Fm.	This study
U-Pb	***41.0**	***0.6**	Zircon (I)	Intermediate ash flow	Palm Park Fm.	This study
U-Pb	41.0	7.4	Whole rock	Porphyritic basalt	None listed	Marvin et al., 1988
U-Pb	***41.3**	***0.7**	Zircon (I)	Intermediate flow (banded)	Palm Park Fm.	This study
U-Pb	***41.6**	***0.7**	Zircon (I)	Intermediate lava flow	Palm Park Fm.	This study
Ar-Ar	41.69	0.12	Biotite (I)	Andesite	Rubio Peak Fm.	McMillan, 2004
Ar-Ar	41.78	0.16	Hornblende (I)	Andesite	Rubio Peak Fm.	McMillan, 2004
K-Ar	42.2	1.6	Biotite (I)	Andesite porphyry	Palm Park Fm	Clemons, 1979
Ar-Ar	42.37	2.59	Hornblende (D)	Andesite lahar	Rubio Peak Fm.	McMillan, 2004
U-Pb	***42.8**	***0.5**	Zircon (I)	Intermediate lava flow	Orejon Andesite	This study
Ar-Ar	43.12	0.19	Plagioclase	Intermediate dike	Palm Park Fm.	Ramos et al., this volume
U-Pb	***43.8**	***0.4**	Zircon (I)	Intermediate lava flow	Orejon Andesite	This study
U-Pb	***44.0**	***1.5**	Zircon (I)	Intermediate lava flow	Orejon Andesite	This study
U-Pb	44.215	0.054	Zircon (I)	Intermediate flow	Orejon Andesite	Rioux et al., 2016
K-Ar	44.4	1.6	Biotite (D)	Laharic tuff breccia	Palm Park Fm.	Hawley et al., 1975
K-Ar	44.7	1.9	Biotite (D)	Dacite	Rubio Peak Fm. (?)	Clemons, 1982
K-Ar	44.8	1.7	Biotite (I)	Andesite	None listed	Lamarre, 1974
U-Pb	***45.0**	***0.7**	Zircon (I)	Ash fall tuff	Palm Park Fm.	This study
Ar-Ar	46.3	0.3	Hornblende (D)	Andesite clast (in lahar)	Rubio Peak Fm.	McMillan, 2004

*New ages from this study; (I) - Igneous; (D) - Detrital

Andesite, and Rubio Peak Formation from south-central New Mexico.

Palm Park Formation

The Palm Park Formation is exposed throughout south-central New Mexico where it crops out in the Doña Ana, Robledo, San Diego, Potrillo, and Caballo Mountains as well as in the Selden and Sleeping Lady Hills and Sierra de las Uvas (Figs. 1, 2). The Palm Park is characterized primarily by coarse- to fine-grained gray, tan, maroon, purple, and green volcaniclastic strata (e.g., lahar deposits with subordinate hyperconcentrated and fluvial sheetflow deposits), volcanic rocks (e.g., lava flows and tuffs), small-volume intrusions (e.g., sills, dikes, plugs, and stocks), and interbedded freshwater limestone and gypsum-bearing lacustrine strata (Kelley and Silver, 1952; Seager et al., 1971; Seager and Hawley, 1973; Seager, 1975; Seager et al., 1975; Seager et al., 1976; Clemons, 1979; Seager, 1981; Mack et al., 1998; Seager et al., 2008; Creitz, 2017). Although there are no complete base-to-top sections of the Palm Park preserved at any one locality, the unit as a whole has a considerable range in thickness (30–915 m), which has been attributed in part to variations in underlying Laramide paleotopography (Seager et al., 1971; Seager and Hawley, 1973; Seager, 1975; Seager et al., 1975; Seager et al., 1976; Clemons, 1979; Seager, 1981; Mack et al., 1998; Seager et al., 2008). In the Las Cruces area, the Palm Park Formation has been documented to be relatively thinner where it overlies the former Laramide topographic high of the Rio Grande uplift and thicker along the south-tilted flank (Figs. 1, 2; Mack et al., 1998).

Prior to this study, there were only a few published K-Ar ages for the Palm Park Formation, including an age of 44.4±1.6 Ma determined from a detrital clast of tuff breccia collected from a lahar deposit (Hawley et al., 1975) and an age of 42.2±1.6 Ma determined from an andesite porphyry (Clemons, 1979). An intermediate dike in the Doña Ana Mountains has a $^{40}Ar/^{39}Ar$ date of 43.12±0.19 Ma (Ramos and Heizler, this volume). Some of the youngest parts of the Palm Park are exposed in the southern Caballo Mountains where late early Chadronian (~36.5–35.7 Ma) vertebrate fossils have been reported (Figs. 1, 3; Lucas, 2015). These fossils include tortoise (aff. Stylemys), hyaenodontid creodont *Hyaenodon horridus*, rhinoceros cf. *Hyracodon* sp., horse *Mesohippus* cf. *M. texanus*, and oreodont *Merycoidodon presidioensis* (Lucas and Williamson, 1993; Lucas et al., 1997; Lucas, 2015). This late early Chadronian age range corresponds with the oldest report-

ed $^{40}Ar/^{39}Ar$ age of 35.69 Ma age from the overlying Bell Top Formation (McIntosh et al., 1991).

Orejon Andesite

The Orejon Andesite is exposed in the southern San Andres Mountains (at Hardscrabble Hill) and in the central and western parts of the Organ Mountains (Fig. 1), where it consists primarily of coarse-grained gray, purple, maroon, and faint blue intermediate volcaniclastic strata (dominantly massive, matrix-supported conglomerate) and volcanic rocks (primarily intermediate lava flows and rare siliceous tuffs) (Glover, 1975; Seager, 1981). There are no complete base-to-top exposures of the Orejon Andesite exposed but the maximum exposed thickness is estimated at ~360 m based on map relationships (Seager, 1981).

Prior to this study, there was only one published U-Pb zircon age of 44.215±0.054 Ma reported from an intermediate flow that occurs in the stratigraphically highest part of the Orejon Andesite near the mouth of Fillmore canyon in the western Organ Mountains (Rioux et al., 2016). Near this same locality (and directly up stratigraphic section), $^{40}Ar/^{39}Ar$ ages of 36.45±0.08, 36.23±0.14, and 36.0±0.16 Ma (Zimmerer and McIntosh, 2013), and U-Pb zircon ages of 36.441±0.020, 36.259±0.016, and 36.215±0.016 Ma (Rioux et al., 2016) have been reported from rocks that make up the oldest parts of the Organ caldera complex. The nature of the contact between the Orejon Andesite and overlying ignimbrites of the Organ caldera appears to be unconformable suggesting prolonged eruptive hiatus between these two units (Fig. 3). At present, there is no biostratigraphic constraint from the Orejon Andesite and this unit is considered roughly coeval with the oldest parts of the Palm Park Formation.

Cleofas Andesite

The Cleofas Andesite crops out in the central part of the Doña Ana Mountains (Fig. 1) and consists primarily of andesite porphyry deposits that range in color from gray, tan, pale purple, dark red, to faint blue in color and exhibit occasional flow-banded textures (Seager et al., 1976; Seager et al., 2008). The thickness of the Cleofas Andesite has yet to be determined and no complete section of the unit is exposed, thus the upper and lower stratigraphic relationship between this unit and the Palm Park Formation is unknown. However, in some localities the Cleofas Andesite appears to be interbedded with volcaniclastic lahar deposits of the Palm Park Formation and flow-banded clasts of Cleofas Andesite can be observed in lahar beds of the Palm Park (Seager et al., 1976). The Cleofas Andesite is considered to be an intermediate, volcanic-dominated member of the Palm Park Formation (W.R. Seager, pers. commun., 2017).

One K-Ar age of 35.9±1.6 Ma has been previously reported from the Cleofas Andesite (Table 1; Clemons, 1979). Stratigraphic relationships in the Doña Ana Mountains support an interpretation where the Cleofas Andesite is likely age equivalent to the middle and uppermost parts of the Palm Park Formation (Seager et al., 2008). $^{40}Ar/^{39}Ar$ age ages from the oldest parts of the overlying Doña Ana caldera, including a 36.04±0.01 Ma age from the Doña Ana Rhyolite and 35.98±0.02 Ma Goat Mountain Rhyolite (Ramos and Heizler, this volume) support an uppermost age limit of ~36 Ma for the Cleofas Andesite and Palm Park Formation (Fig. 3).

Rubio Peak Formation

The Rubio Peak Formation in south-central New Mexico crops out in the Good Sight Mountains and Uvas Valley as well as the eastern Black and Cooke's Ranges (Fig. 1), where it is made up primarily of coarse- to fine-grained volcaniclastic strata (e.g., lahar, hyperconcentrated, and fluvial sheetflow deposits) and subordinate volcanic rocks (e.g., lava flows, tuffs, dikes, plugs, and stocks; Clemons, 1979). The maximum thickness of the Rubio Peak Formation in the Goodsight Mountains and Cooke's Range has been estimated to be ~1000 m (Clemons, 1979; Elston, 1957). Alluvial facies of the Rubio Peak and Palm Park Formation are thought to be interbedded in the Good Sight Mountains and Uvas Valley, indicating the Palm Park and Rubio Peak Formation are correlative but likely derived from different volcanic vents during the same period of time (Elston, 1957; Clemons, 1979).

There are a number of K-Ar and $^{40}Ar/^{39}Ar$ ages that have been reported previously from the Rubio Peak Formation in south-central New Mexico that fall within a range of 46.3±0.3 Ma to 36.4±2.3 Ma (Table 1; Marvin and Cole, 1978; Clemons, 1979; McMillan, 2004). The middle and upper part of this age range is also partly supported biostratigraphically by occurrences of Duchesnean (~40–37 Ma) and late early Chadronian (~36.5–35.7 Ma) vertebrate mammal fossils in the southern Black Range (Lucas, 2015). These fossils include a brontothere jaw *Duchesneodus uintensis*, rodent *Jaywilsonomys ojinagaensis*, oromerycid *Montanatylopus matthewi*, perissodactyl (possibly a brontothere), and a possible hypertragulid artiodactyl (Lucas, 2015). These fossil ages together with the $^{40}Ar/^{39}Ar$ age of 35.69 Ma for Ash Flow Tuff 3 of the Bell Top Formation (McIntosh et al., 1991) further support an upper bounding age of the Rubio Peak Formation as late Eocene. Existing radioisotopic ages from the Rubio Peak Formation, together with late early Chadronian vertebrate fossils within the Rubio Peak and the oldest radioisotopic age from the overlying Bell Top Formation (McIntosh et al., 1991), support an age range for the Rubio Peak between 46–36 Ma.

METHODS

A total of nine igneous zircon samples were collected from parts of the Palm Park Formation (N=6) and Orejon Andesite (N=3) in south-central New Mexico for determination of U-Pb zircon ages (n=247 analyses) (Figs. 1, 3). Table 2 provides a summary of all sample localities. Zircon crystals were extracted from samples at New Mexico State University using standard heavy-mineral separation techniques (i.e., utilizing a Chipmunk jaw crusher, Bico pulverizer, 30-micron mesh sieve, Gemini table, Frantz separator, sodium polytungstate,

TABLE 2. Summary of GPS locations for all U-Pb igneous samples from this study.

Sample and n=analyses	Field Locality	Formation	Lat./Long.	Age (Ma)	±(Ma)
PALMP(SU/BT)-01 (n=40)	Sierra de las Uvas - Bell Top Mtn.	Palm Park Fm.	32.48575/-107.11977	39.6	0.5
PALMP(RB/FC)-08 (n=30)	Robledo Mtns. - Faulkner Canyon	Palm Park Fm.	32.47821/-106.94792	41.0	0.6
PALMP(RB/FC)-01 (n=32)	Robledo Mtns. - Faulkner Canyon	Palm Park Fm.	32.46006/-106.97142	41.0	0.6
PALMP(DA/CC)-01 (n=38)	Doña Ana Mtns. - Cleofas Canyon	Palm Park Fm.	32.46156/-106.83753	41.3	0.7
PALMP(DA/CC)-05 (n=31)	Doña An Mtns. - Cleofas Canyon	Palm Park Fm.	32.46318/-106.84364	41.6	0.7
OREJON(OR/FL)-01 (n=20)	Organ Mtns. - Fillmore Canyon	Orejon Andesite	32.34398/-106.56825	42.8	0.5
OREJON(OR/FL)-02 (n=30)	Organ Mtns. - Fillmore Canyon	Orejon Andesite	32.34354/-106.58386	43.8	0.4
OREJON(OR/FL)-03 (n=18)	Organ Mtns. - Fillmore Canyon	Orejon Andesite	32.33712/-106.59317	44.0	1.5
PALMP(RB/AC)-02 (n=8)	Robledo Mtns. - Apache Canyon	Palm Park Fm.	32.34792/-106.88124	45.0	0.7

and methylene iodide). Zircons were then placed into a one-inch epoxy mount with zircon standards R33, Sri Lanka (SL), and FC at the Arizona Laserchron Center in Tucson, Arizona. Zircon mounts were sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to analysis. Cathodoluminescence images were acquired to assist in the identification of locations for ablation pits at the cores of zircons.

All U-Pb analyses of igneous zircons were conducted by laser ablation inductively coupled mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center. Data produced from zircon analyses was imported in an Excel spreadsheet ("agecalc"), which corrects data, calculates ages, uncertainties, and error correlations (Gehrels et al., 2008). In "agecalc" raw data is first corrected for background intensities and excess ^{204}Hg that is indicated by above-background ^{202}Hg. Next, for each analysis, the errors in determining ^{206}Pb/^{238}U and ^{206}Pb/^{204}Pb result in the application of a measurement error of ~1-2% (at 2σ) in the ^{206}Pb/^{238}U age. The errors in measurement of ^{206}Pb/^{207}Pb and ^{206}Pb/^{204}Pb also result in ~1-2% (at 2σ) uncertainty in age for grains that are >1.0 Ga, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb ages occurs at ~1.2 Ga. Correction of common lead is done by using the Hg-corrected ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers, (1975). Uncertainties of 1.5 for ^{206}Pb/^{204}Pb and 0.3 for ^{207}Pb/^{204}Pb are applied to these compositional values based on variation of Pb composition in modern crystalline rocks. Inter-element fractionation of Pb/U is generally ~5%, whereas apparent fractionation of Pb isotopes is generally <0.2%. Analysis of standards is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1-2% (2σ) for both ^{206}Pb/^{207}Pb and ^{206}Pb/^{238}U ages.

The data from each sample analysis was filtered then applied to a weighted mean calculation, which weights each zircon analyzed according to the square of its uncertainty and generates a final age with uncertainty and mean square of weighted deviates (MSWD). For the purposes of this study (and depending on zircon yield from each sample), 30-50 crystals were analyzed from each sample to increase precision (Fig. 4).

RESULTS

Our study resulted in one new age from the Palm Park Formation in the Sierra de las Uvas (Bell Top mountain locality), three new ages from the Robledo Mountains (Apache and Faulkner canyons), two new ages from the Doña Ana Mountains (Cleofas Canyon), and three new ages from the Orejon Andesite in the Organ Mountains (Fillmore Canyon) (Figs. 1, 3, 4). All samples were collected from discrete stratigraphic horizons in the Palm Park Formation and Orejone Andesite (Figs. 3, 4). Ages are presented below (at 2σ error) in the context of the four geographic field localities in this study. A summary of all geochronologic data collected from this study can be found in the online Data Repository (http://nmgs.nmt.edu/repository).

Sample PALMP(RM/AC)-02 yielded an age of 45.0±0.7 Ma (n=8 of 31; MSWD=1.80; Fig. 4, Table 1) and was collected from an ash fall-tuff that stratigraphically underlies limestone and gypsum-bearing strata that make up the lower part of the Palm Park Formation in the Robledo Mountains (near Apache Canyon; Fig. 5A). This is one of the oldest reported ages from the Palm Park Formation in south-central New Mexico (Table 1). Of the 31 zircon crystals analyzed from this sample, 23 yielded Meso- and Paleoproterozoic ages that were not used for age determination. Sample PALMP(RB/FC)-08 yielded an age of 41.0±0.6 Ma (n=30 of 34; MSWD=0.46; Fig. 4, Table 1) and PALMP(RB/FC)-01 yielded a nearly identical age of 41.0±0.6 Ma (n=32 of 35; MSWD=0.24; Fig. 4, Table 1). PALMP(RB/FC)-08 was collected from and block-and-ash flow from the Faulkner Canyon field locality (Fig. 5B). Of the 30 zircon crystals analyzed from this sample, 4 yielded Mesoproterozoic ages that were not used for age determination. PALMP(RB/FC)-01was collected from an intermediate porphyry in the Palm Park Formation in Faulkner Canyon of the northern Robledo Mountains. This sample contained 2 zircon crystals that yielded Mesoproterozoic ages and 1 crystal that yielded a Jurassic age.

Samples OREJON(OR/FL)-03, OREJON(OR/FL)-02, and OREJON(OR/FL)-01 yielded ages of 44.0±1.5 (Fig. 4, Table 1; n=18 of 23; MSWD=0.33), 43.8±0.4 (Fig. 4, Table 1; n=30

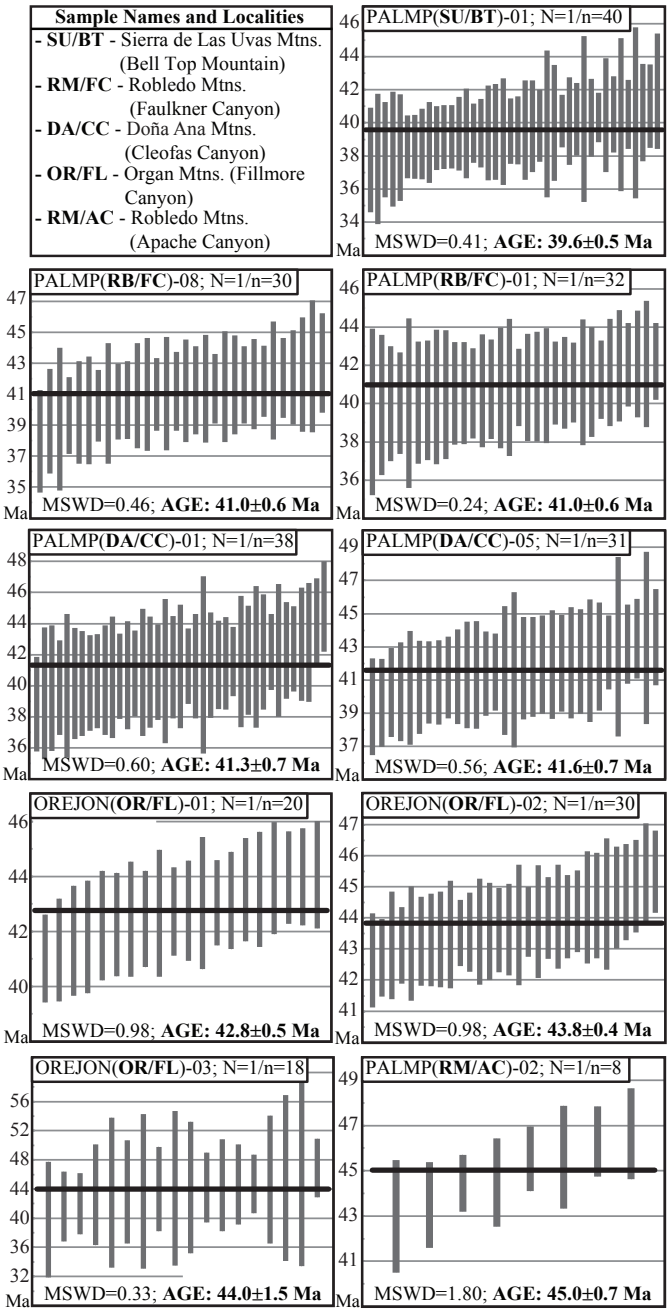


FIGURE 4. Summary of new U-Pb igneous zircon ages from the Palm Park Formation and Orejon Andesite in south-central New Mexico. Note samples are ordered from oldest (base of figure) to youngest (top of figure).

of 34 ; MSWD=0.98), and 42.8±0.5 Ma (Fig. 4, Table 1; n=20 of 27; MSWD=0.98), respectively. Each of these samples was collected from discrete intermediate lava flows in the Orejon Andesite near Fillmore Canyon in the Organ Mountains (Fig. 5C). Sample OREJON(OR/FL)-03 (44.0±1.5 Ma) was collected near the contact with oldest rocks of the Organ caldera complex (i.e., Cueva Tuff; Fig. 5C). Of the 18 zircon crystals analyzed from OREJON(OR/FL)-03, 5 yielded Mesoproterozoic ages that were not used for age determination. From the 34 total zircon crystals analyzed from OREJON(OR/FL)-02, 4 yielded ages that were Meso- and Paleoproterozoic and excluded from age determination. Sample OREJON(OR/FL)-01 had 4 crystals with Paleoproterozoic ages that were not included for age determination.

Samples PALMP(DA/CC)-05 and PALMP(DA/CC)-01 yielded ages of 41.6±0.7 (Fig. 4, Table 1; n=31 of 34; MSWD=0.56) and 41.3±0.7 Ma (Fig. 4, Table 1; n=38 of 49; MSWD=0.60), respectively and were collected from an intermediate flow and banded flow in the Palm Park Formation that crop out in Cleofas Canyon of the western Doña Ana Mountains (Fig. 5D). Of the 31 zircon crystals analyzed from PALMP(DA/CC)-05, 2 yielded Mesoproterozoic ages that were not used for age determination. Sample PALMP(DA/CC)-01 contained 9 zircon crystals of Meso- and Paleoproterozoic age that were not included in age determination.

Sample PALM(SU/BT)-01 yielded an age of 39.6±0.5 Ma (Fig. 4, Table 1; n=40 of 47; MSWD=0.41) and was collected from an ash-fall tuff near the top of the Palm Park Formation in the Bell Top Mountain locality of the eastern Sierra de las Uvas (Fig. 5E). This is the youngest reported age from the Palm Park Formation in south-central New Mexico (Table 1). This sample contained 4 zircon crystals that yielded Mesoproterozoic ages and 1 crystal that yielded a Neoproterozoic age, and 1 crystal with a Cretaceous age.

DISCUSSION

New U-Pb zircon ages from the Palm Park Formation and Orejon Andesite constrain the duration of intermediate volcanism and sedimentation that took place after Laramide deformation and prior to the onset of the Rio Grande rift at ~36 Ma in south-central New Mexico. U-Pb ages from this study combined with existing ages from the Palm Park Formation (including the Cleofas Andesite) in the Doña Ana, Organ, San Andres, Caballo, Robledo, Potrillo, and Sierra de las Uvas Mountains (Table 2), and vertebrate mammal fossil occurrences from the Palm Park Formation in the southern Caballo Mountains (e.g., Lucas and Williamson, 1993; Lucas et al., 1997; Lucas, 2015) help bracket this phase of volcanism and sedimentation to a ~10 my period during the middle–late Eocene (~46–36 Ma; Figs. 3, 6). A near-continuous, coeval record of intermediate volcanism and volcaniclastic sedimentation is recorded in middle–late Eocene rocks of the Rubio Peak Formation in the Goodsight Mountains, Black Range and Cooke's Range in south-central New Mexico (Fig. 6; e.g., Elston, 1957; Clemons, 1979; McMillan, 2004).

It is important to note that although this study helps with constraining the duration of middle–late Eocene volcanism and volcaniclastic sedimentation in south-central New Mexico, the age, location, and number of individual stratovolcano vents that sourced the Palm Park Formation and equivalent units remains unclear. It is possible that these intermediate rocks were sourced from a series of discrete volcanic vents that may have ranged in age as well proximity to the Las Cruces area (e.g., Ramos et al., this volume). The latter is especially true with ash-fall tuffs that could have been far-traveled from vent sources outside of present-day southern New Mexico. Thus, the age of these rocks in the Las Cruces area could differ in age

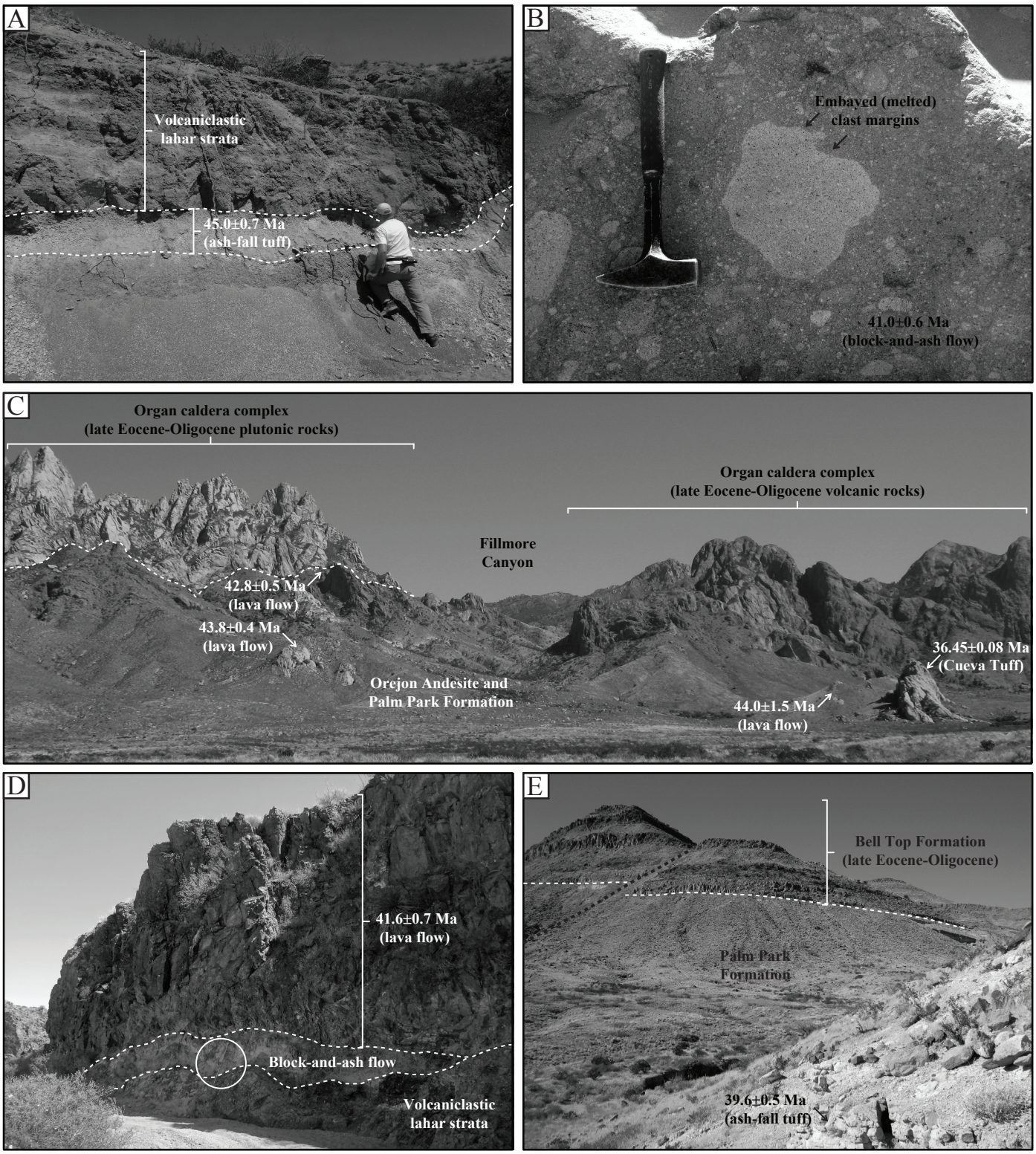


FIGURE 5. Field photos of the Palm Park Formation and Orejon Andesite in south-central New Mexico. **A**) Interbedded volcanic (ash fall) and volcaniclastic (lahar) strata of Palm Park Formation from the Apache Canyon locality in the northern Robledo Mountains. Age from ash-fall tuff at this locality represents one of the oldest reported ages from the Palm Park Formation. Geologist for scale. **B**) Block-and-ash flow deposit with embayed (melted) clast margins from the Faulkner Canyon locality in the northern Robledo Mountains. Rock hammer for scale. **C**) Panorama view to the east of the Organ Mountains and Fillmore Canyon field locality. Note late Eocene–Oligocene plutonic rocks (left) and volcanic rocks (right) of the Organ caldera complex including oldest Cueva Tuff unit. Three new ages are reported here from lava flows in the Orejon Andesite (foreground). **D**) Interbedded volcanic (lava flow and block-and-ash flow) and volcaniclastic (lahar) strata from the Cleofas Canyon locality in the west-central Doña Ana Mountains. White circle denotes 1.5-m Jacob Staff for scale. **E**) View to the northwest of the uppermost Palm Park Formation (lower) and overlying Bell Top Formation in the Bell Top mountain locality of the Sierra de las Uvas. White dashed line denoted location of contact between the Palm Park Formation and Bell Top Formation. Black dash line denotes location of minor fault and corresponding offset. Age from ash-flow tuff at this locality represent the youngest reported age from the Palm Park Formation.

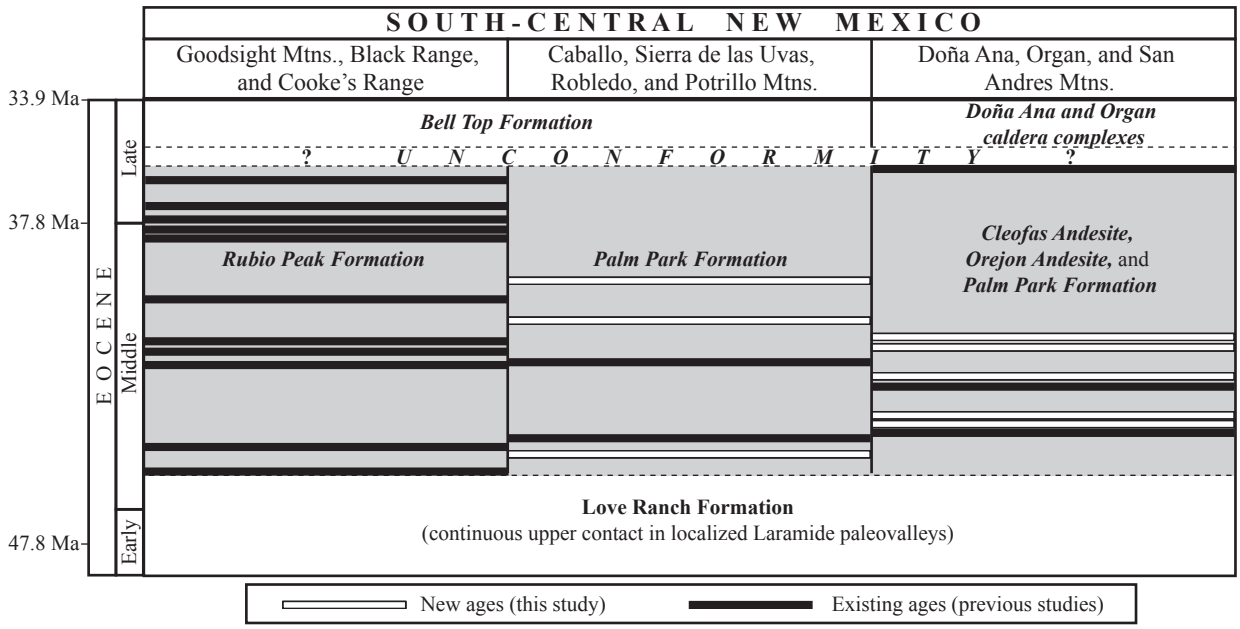


FIGURE 6. Generalized stratigraphic summary including all existing ages from volcanic rocks of the Palm Park Formation, Orejon Andesite, Rubio Peak Formation and Cleofas Andesite throughout south-central New Mexico. New and existing ages correspond to all ages summarized on Appendix 1.

slightly compared to the Rubio Peak Formation to the west and northwest and possibly with other Palm Park localities to the north (e.g., Caballo Mountains). Future work aimed at isolating the location and ages of stratovolcano vent sources should promote a better understanding of what the middle–late Eocene volcanic landscape may have looked like in southern New Mexico just prior to the onset of the Rio Grande rift.

Although a much more regional study is needed to better understand the plate-scale mechanism that drove Eocene magmatism throughout the southwestern U.S., it is worth discussing our new ages in the context of early–middle Eocene flat slab subduction and evolution of accompanying mantle wedge and the subsequent onset of bimodal volcanism and initiation of the Rio Grande rift. It is generally accepted that flab slab subduction associated with the Laramide orogeny continued through much of the early–middle Eocene until at least ca. 45 Ma when subduction began to terminated and the Farallon slab underwent rollback, delamination, and eventual foundering into the asthenosphere (e.g., Coney and Reynolds, 1977; Humphreys, 1995, 2009; Dickinson, 2009). The synorogenic Love Ranch Formation and overlying, post orogenic rocks of the Palm Park Formation, Orejon Andesite, and equivalent rocks summarized in this study preserve the stratigraphic record of this transition in southern New Mexico (e.g., Seager, 2005). Foundering of the Farallon slab resulted in widespread bimodal volcanism associated with the "ignimbrite fare-up" which was likely driven by partial melting of upper-mantle sources after subduction ceased (e.g., Humphreys et al, 2003; Farmer et al., 2008; Roy et al., 2009). The onset of bimodal volcanism throughout southern New Mexico is recorded by latest Eocene–Oligocene rocks of the Bell Top Formation and equivalent units. Much of the early–late Oligocene was marked by magmatism associated by asthenospheric upwelling likely associated with detachment of the Farallon slab (e.g., Moucha et al., 2008; van Wijk et al., 2008; Ricketts, 2016). By latest Oligocene time (ca. 25 Ma) widespread magmatism and volcanism gave way to extension and brittle deformation associated with the Rio Grande rift (e.g., Ricketts, 2016).

CONCLUSIONS

Although the exact timing of cessation of Laramide orogenesis and subsequent magmatism associated with slab foundering and asthenospheric upwelling likely varied throughout the southwestern U.S., we interpret middle–late Eocene intermediate volcanic rocks for the Palm Park Formation, Orejone Andesite, and equivalent strata to represent the first phase of post-orogenic magmatism associated with upper-mantle sources during initial foundering of the Farallon plate beneath New Mexico. At present, it is unclear whether this magmatism initiated prior to ~45 Ma due largely to the fact that the stratigraphic base of the Palm Park Formation has yet to be identified in southern New Mexico. It is also has yet to be determined how this phase of intermediate volcanism in southern New Mexico transitioned into latest Eocene–Oligocene bimodal volcanism and onset of the Rio Grande rift. Future work focused on age-equivalent rocks throughout the southwestern U.S. should promote a better understanding on the lithosphere-scale mechanisms that were driving mid–late Eocene magmatism just after Laramide orogenesis.

ACKNOWLEDGMENTS

Results from this study were part of a M.S. project completed by Ryan Creitz at New Mexico State University in August of 2017. Financial support for this project was provided in part

by student grants from the American Association of Petroleum Geologists, Colorado Scientific Society, Geological Society of America, New Mexico Geological Society, and New Mexico State University's College of Arts & Sciences and Department of Geological Sciences. We are grateful for earlier work by Russell Clemons, John Hawley, Frank Kottlowski, and William Seager that provided a geologic field context for this project. This manuscript benefited from discussions with Emily Johnson, Nancy McMillan, William Seager, and James Witcher. We thank George Gehrels, Mark Pecha, Nicky Giesler, Chelsi White, and Kojo Plange of the University of Arizona LaserChron Center (supported through NSF-EAR #1649254) for assistance with collecting and reducing U-Pb data. Jason Ricketts and Matthew Zimmerer provided valuable reviews that helped improve an earlier draft of this manuscript.

REFERENCES

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 geochronology: Geological Society of America Bulletin, v. 129, p. 1209–1226.

Bevington, P.R., and Robinson, K.D., 1969, Data Reduction and Error Analysis for the Physical Sciences: New York, McGraw-Hill, 336 p.

Cather, S.M., 1990, Stress and volcanism in the northern Mogollon-Datil volcanic field, New Mexico: Effects of the post-Laramide tectonic transition: Geological Society of America Bulletin, v. 102, p. 1447-1458.

Cather, S.M., and Johnson, B.D., 1984, Eocene tectonics and depositional setting of west-central New Mexico and eastern Arizona: New Mexico Bureau of Mines and Mineral Resources Circular 192, 33 p.

Cather, S.M., McIntosh, W., and Chapin, C.E., 1987, Stratigraphy, age, and rates of deposition of the Datil Group (upper Eocene-lower Oligocene), west-central New Mexico: New Mexico Geology, v. 9, no. 3, p. 50-54.

Clemons, R.E., 1975, Petrology of the Bell Top Formation: New Mexico Geological Society, Guidebook 26, p. 123–130.

Clemons, R.E., 1979, Geology of Good Sight Mountains and Uvas Valley, southwest New Mexico, Socorro, NM, New Mexico Bureau of Mines & Mineral Resources, 31 p.

Clemons, R.E., 1982 Geology of Massacre Peak quadrangle: Luna County, New Mexico: New Mexico Bureau of Mines and Mineral Reserouces, Geologic Map, v. 51.

Clinkscales, C.A., and Lawton, T.F., 2014, Timing of Late Cretaceous shortening and basin development, Little Hatchet Mountains, southwestern New Mexico, USA–implications for regional Laramide tectonics: Basin Research, v. 24, p. 453–472.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406.

Creitz, R.H, 2017, Sedimentology, stratigraphy, and geochronology from middle–late Eocene volcanic and volcaniclastic strata of the Palm Park Formation and Orejon Andesite, south-central New Mexico [M.S. Thesis]: Las Cruces, New Mexico State University, 183 p.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, p. 105–168.

Dickinson, W.R., 2004, Evolution of the North American cordillera: Annual Review of Earth Planetary Science, v. 32, p. 13–45.

Dickinson, W.R., 2009, Anatomy and global context of the North American Cordillera, in Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subdution, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 1–29.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039.

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny: Geological Society of America Memoirs, v. 151, p. 355–366.

Elston, W.E., 1957, Geology and Mineral Resources of Dwyer Quadrangle: Grant, Luna, and Sierra Counties, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources, Bulletin 38, 86 p.

Farmer, G.L., Bailley, T., and Elkins-Tanton, L.T., 2008, Mantle source volumes and the origin of the mid-Tertiary ignimbrite flare-up in the southern Rocky Mountains, western U.S.: Lithos, v. 102, p. 279–294.

Gehrels, G.E., 2010, U-Th-Pb analytical methods: Arizona LaserChron Center, University of Arizona, p. 1–13.

Gehrels, G.E., Valencia, V.A., and Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry: Geochemistry, Geophysics, Geosystems, v. 9, no. 3, p. 1–13.

Glover, T.J., 1975, Geology of the central Organ Mountains Doña Ana County, New Mexico: New Mexico Geological Society, Guidebook 26, p. 157–161.

Hawley, J.W., Seager, W.R., and Clemons, R.E., 1975, Third day-road log from Las Cruces to north Mesilla Valley, Cedar Hills, San Diego Mountain, and Rincon area: New Mexico Geological Society, Guidebook 26, p. 35–53.

Humphreys, E., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987–990.

Humphreys, E., 2009, Relation of flat slab subduction to magmatism and deformation in the western United States, *in* Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subdution, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 85–98.

Humphreys, E., Hessler, E., Dueker, K., Erslev, E., Farmer, G.L., and Atwater, T., 2003, How Laramide-age hydration of North America by the Farallon slab controlled subsequent activity in the wesern U.S.: International Geology Review, v. 45, p. 575–595.

Kelley, V.C., and Silver, C., 1952, Geology of the Caballo Mountains: With special reference to regional stratigraphy and structure and to mineral resources, including oil and gas: Albuquerque, University of New Mexico Press, University of New Mexico Publications in Geology, no. 4, 286 p.

Lawton, T.F, and Clemons, R.E., 1992, Klondike Basin—late Laramide depocenter in southern New Mexico: New Mexico Geology, v. 14, no. 1, p. 1–7.

Lawton, T.F., Basabilvazo, G.T., Hodgson, S.A., Wilson, D.A., Mack, G.H., McIntosh, W.C., Lucas, S.G., and Kietzke, K.K., 1993, Laramide stratigraphy of the Little Hatchet Mountains, southwestern New Mexico: New Mexico Geology, v. 15, no. 1, p. 9–15.

Lawton, T.F., and McMillan, N.J., 1999, Arc abandonement as a cause for passive continental rifting: Comparision of the Jurassic Mexican Boarderland Rift and the Cenozoic Rio Grande rift: Geology, v. 27, p. 779–782.

Lamarre, A.L., 1974, Fluorite in jasperoid of the Salado Mountains – Significance to metallogeny of the western United States [M.S. Thesis]: London, University of Western Ontario, 134 p.

Loring, A., and Loring, R., 1980, K/Ar ages of middle Tertiary igneous rocks from southern New Mexico: Isochron/West, no. 28, p. 17–18.

Lucas, S.G., Estep, J.W., Williamson, T.E., and Morgan, G.S., 1997, New Mexico's Fossil Record 1: New Mexico Museum of Natural History and Science, Bulletin 11, 143 p.

Lucas, S.G., and Williamson, T.E., 1993, Eocene vertebrates and late Laramide stratigraphy of New Mexico: New Mexico Museum of Natural History and Science, Bulletin 2, p. 145–158.

Lucas, S.G., 2015, Eocene Fossil Vertebrates of New Mexico: New Mexico Museum of Natural History and Science, v. 68, p. 149–158.

Mack, G.H., Kottlowski, F.E., and Seager, W.R., 1998, The stratigraphy of south-central New Mexico: New Mexico Geological Society, Guidebook 49, p. 135–154.

Mack, G.H., and Clemons, R.E., 1988, Structural and stratigraphic evidence for the Laramide (early Tertiary) Burrow uplift in southwestern New Mexico: New Mexico Geological Society, Guidebook 39, p. 59–66.

Mack, G.H., Nightengale, A.L., Seager, W.R., and Clemons, R.E., 1994, The Oligocene Goodsight-Cedar Hills half graben near Las Cruces and its implications to the evolution of the Mogollon-Datil volcanic field and to the southern Rio Grande rift: Guidebook of the Mogollon slope, west-central New Mexico and east-central Arizona: New Mexico Geological Society, Guidebook, v. 45, p. 135–142.

Marvin, R. and Cole, J.C., 1978, Radiometric ages: Compilation A: US Geological Survey, Isochron/West, v. 22, p. 3–14.

Marvin, R., Mehnert, H.H., and Naeser, C.W., 1988, U.S. Geological Survey radiometric ages, Compilation C, Part two, Arizona and New Mexico: Isochron/West, no. 51, p. 5–13.

McIntosh, W.C., Kedzie, L.L., and Sutter, J.F., 1991, Paleomagnetism and $^{40}Ar/^{39}Ar$ ages of ignimbrites, Mogollon-Datil volcanic field, southwestern New Mexico: New Mexico Bureau of Mines & Mineral Resources, Bulletin 135, 79 p.

McMillan, N.J., 2004, Magmatic record of Laramide subduction and the transition to Tertiary extension: Upper Cretaceous through Eocene igneous rocks of New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico, A Geologic History: New Mexico Geological Society, Special Publication, v. 11, p. 249–270.

McMillan, N.J., Dickin, A.P., and Haag, D., 2000, Evolution of magma source regions in the Rio Grande rift, southern New Mexico: Geological Society of America Bulletin, v. 112, no. 10, p. 1582–1593.

Moucha, R., Forte, A.M., Rowley, D.B., Mitrovica, J.X., Simmons, N.A., and Grand, S.P., 2008, Mantle convection and recent evolution of the Colorado Plateau and the Rio Grande rift valley: Geology, v. 36, p. 439–442.

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico, scale 1:500,000.

Nummedal, D., 2004, Tectonic and eustatic controls on upper Cretaceous stratigraphy of northern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico, A Geologic History: New Mexico Geological Society, Special Publication, v. 11, p. 169–182.

Postma, G., 1986, Classification for sediment gravity-flow deposits based on flow conditions during sedimentation: Geology, v. 14, no. 4, p. 291–294.

Ramos, F.C., and Heizler, M.T., *this volume*, Age relationships of igneous rocks in the Doña Ana Mountains: New Mexico Geological Society, Guidebook 69.

Ramos, F.C., Jacobs, M., Hampton, B.A., *this volume,* Sr and Pb isotope variations of feldspars in the middle to late Eocene Palm Park Formation and Orejon Andesite: Implications for regional variability and magmatic source characteristics: New Mexico Geological Society, Guidebook 69.

Ricketts, J.W., Kelley, S.A., Karlstrom, K.E., Schmandt, B., Donahue, M.S., and van Wijk, J., 2016, Synchronous opening of the Rio Grande rift along its entire length at 25–10 Ma supported by apatite (U-Th)/He and fission-track thermochronology, and evaluation of possible driving mechanisms: Geological Society of America Bulletin, v. 128, p. 397–424.

Rioux, M., Farmer, G.L., Bowring, S.A., Wooton, K.M., Amato, J.M., Coleman, D.S., and Verplanck, P., 2016, The link between volcanism and plutonism in epizonal magma systems: High-precision U-Pb geochronology from the Organ Mountains caldera and batholith: New Mexico: Contributions to Mineralogy and Petrology, v. 171, p. 1–22.

Roy, M., Jordan, T.H., and Pederson, J., 2009, Colorado Plateau magmatism and uplift by warming of heterogeneous lithosphere: Nature, v. 459, p. 978–982.

Seager, W.R., 1975, Middle to late Tertiary geology of Cedar Hills-Selden Hills area, New Mexico: New Mexico Bureau of Geology Circular, no. 133, p. 24.

Seager, W.R., 1981, Geology of Organ Mountains and southern San Andres mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 36, 97 p.

Seager, W.R., 2004, Laramide (Late Cretaceous–Eocene) tectonics of southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico, A Geologic History: New Mexico Geological Society, Special Publication, v. 11, p. 183–202.

Seager, W.R., Clemons, R.E., and Hawley, J.W., 1975, Geology of Sierra Alta Quadrangle, Doña Ana County, New Mexico: New Mexico Bureau of Mines & Mineral Resources, Bulletin 102, 57 p .

Seager, W.R., and Hawley, J.W., 1973, Geology of Rincon quadrangle, New Mexico: New Mexico Bureau of Mines & Mineral Resources, Bulletin 101, 42 p.

Seager, W.R., Hawley, J.W., and Clemons, R.E., 1971, Geology of San Diego Mountain area, Doña Ana County, New Mexico: New Mexico State Bureau of Mines and Mineral Resources, Bulletin 97, 38 p

Seager, W.R., Kottlowski, F.E., and Hawley, J.W., 1976, Geology of Doña Ana Mountains, New Mexico, New Mexico Bureau of Mines & Mineral Resources, Circular 147, 36 p.

Seager, W.R., Kottlowski, F.E., and Hawley, J.W., 2008, Geologic Map of the Robledo Mountains and Vicinity, Dona Ana County, New Mexico: New Mexico Bureau of Geology & Mineral Resources, Open-File Report 509.

Seager, W.R., Mack, G.H., and Lawton, T.F., 1997, Structural kinematics and depositional history of a Laramide uplift-basin pair in southern New Mexico: Implications for development of intraforeland basins: Geological Society of America Bulletin, v. 109, no. 11, p. 1389–1401.

Seager, W.R., Mack, G.H., Raimonde, M.S., and Ryan, R.G., 1986, Laramide basement-cored uplift and basins in south-central New Mexico: New Mexico Geological Society, Guidebook 37, p. 123–130.

Thompson III, S., 1982, Oil and gas exploration wells in southwestern New Mexico: New Mexico Bureau of Mines & Mineral Resources, Open-file Report 181, 18 p.

van Wijk, J., van Hunen, J., and Goes, S., 2008, Small-scale convetion during continental rifting: Evidence from the Rio Grande rift: Geology, v. 36, p. 575–578.

Zimmerer, M.J., and McIntosh, W.C., 2013, Geochronologic evidence of upper-crustal in situ differentiation: Silicic magmatism at the Organ caldera complex, New Mexico: Geosphere, v. 9, no. 1, p. 155–169.

Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2018004



A javelina crossing the road below Leasburg Dam. Photograph by Peter A. Scholle.