

Geologic Map of the Sierra Fijardo 7.5-Minute Quadrangle, Sierra and Socorro Counties, New Mexico

By

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INTRODUCTION

This report accompanies the *Geologic Map of the Sierra Fijardo 7.5-minute Quadrangle, Sierra and Socorro Counties, New Mexico* (Goughnour et al., 2025; referred to herein as “the map area” or “the quadrangle”). Its purpose is to discuss the geologic setting and geologic history of the map area, and to identify and explain significant stratigraphic relationships and geomorphic and structural features discovered during mapping. In particular, we describe the depositional history of the map units in greater detail than is possible on the map sheet. Appendices and a full description of map units are presented at the end of this report.

The map area contains a complicated, often interfingering sequence of Paleogene and Neogene volcanic and volcanoclastic deposits, including several regional ignimbrites erupted from the Mogollon-Datil volcanic field (MDVF; Osburn and Chapin, 1983; Elston, 1984; Cather et al., 1987; McIntosh et al., 1991; Chapin et al., 2004). Although the quadrangle has been mapped previously at 1:36,206 (Farkas, 1969), this small scale was not sufficient to identify these regional ignimbrites. Identifying and dating these ignimbrites is of particular interest because regional stratigraphic correlations across the MDVF have proved challenging due to faulting and lithologic similarities among the volcanic units (McIntosh et al., 1991). Additionally, the source areas of some of these regional ignimbrites have not yet been identified (McIntosh et al., 1992), and detailed mapping of these units could provide insight into the location of their source calderas. An illustrative example is the Luna Park Tuff, which is a widespread unit on this quadrangle whose source is still unknown. This map was initiated, completed, and published by the New Mexico Bureau of Geology and Mineral Resources as part of its mission of creating accurate, up-to-date maps of the state’s geology and resource potential. The map area was

selected at the suggestion of the New Mexico STATEMAP Advisory Committee in its 2023 meeting.

Geographic and Tectonic Setting

The Sierra Fijardo quadrangle covers around 100 km² in south-central New Mexico, approximately 30 km north of the town of Truth or Consequences and 8 km southeast of Vicks Peak. The mapping area is drained by several small, southeast-flowing drainages, including Aragon Wash, Lumber Canyon, and Peñasco Canyon (Fig. 1).

Within the quadrangle, there are two main informal physiographic regions (Fig. 1): (1) the northern hilly terrain of the southernmost San Mateo Mountains and (2) a southern, southeast-sloping piedmont. Several prominent landmarks in the mapping area serve as reference points in this report, including (1) Peñasco Peak, the tallest peak in the map area at 1,982 m, (2) Rimrock Ridge (1,941 m maximum elevation) on the east side of the map area, and (3) Flying X Ranch, which lies west of the center of the map area. The southern piedmont is dominated by Chihuahuan creosote scrubland, whereas the higher-elevation northern hills are dominated by grass and sparse juniper.

Tectonically, the Sierra Fijardo quadrangle lies on the eastern edge of the MDVF and the western edge of the extensional Rio Grande rift zone. Directly to the northwest of the quadrangle lies the Nogal Canyon caldera (Deal and Rhodes, 1976; Hermann, 1986; McLemore, 2012), which is the source of the widespread Vicks Peak Tuff. Although some faulting in the northern portion of the quadrangle may be indirectly related to the collapse of the Nogal Canyon caldera, the majority of the faults in the map area are likely related to Rio Grande

rifting. The southern piedmont portion of the quadrangle is part of the Engle basin of the Rio Grande Rift (Chapin, 1971).

Previous Work

The first major mapping effort that encompasses the Sierra Fijardo quadrangle was the PhD dissertation of Farkas (1969), who covered a large area of the southern San Mateo Mountains and established a workable regional stratigraphic framework of the volcanic rocks, much of which we have used in our study. Sections of the Sierra Fijardo quadrangle have also been subject to additional studies focused on mineral resources and structure. Foruria (1984) included the very western edge of the quadrangle in his geologic and precious metals study of the southern San Mateo Mountains, but he did not identify any major resources within the Sierra Fijardo quadrangle.

Mapping efforts by Koning et al. (2014) in the Monticello quadrangle to the west of Sierra Fijardo have proved invaluable for this report. We carry over many of the stratigraphic designations used by Koning et al. (2014), including abandoning the Rock Springs Formation in favor of raising the associated regional tuffs to formation rank. We differ from Koning et al. (2014) in that we remove all volcanoclastic sediments from the Red Rock Ranch Formation and place them into the Spears Group, at the recommendation of Cather et al. (1994).

Geologic overviews of the larger region, especially the San Mateo Mountains, provide useful information and a context for our study. Such overviews include those of the region's calderas (Ferguson et al., 2012), general geology and minerals (McLemore, 2012), and the stratigraphy and structure of the Winston graben (coinciding with upper Alamosa Creek) to the

northwest (Koning and Rinehart, 2021). Outside of the map area, additional notable mapping and volcanic studies in the southern San Mateo Mountains include maps from Furlow (1965), Atwood (1982), Ferguson (1986), and Lynch (2003). Studies focusing on mineral resources in the vicinity of Sierra Fijardo include those of Cox (1985) in the San Jose mining district, Davis (1988) at Aragon Hill, and McLemore (2010) at the Ojo Caliente 2 mining district.

A research topic driving past study has been the location of the southern edge of the Nogal Canyon caldera, which is the proposed source caldera for the Oligocene Vicks Peak Tuff. Deal and Rhodes (1976) used the presence of rhyolite intrusions at Peñasco Peak in the Sierra Fijardo quadrangle and Aragon Hill in the Monticello quadrangle to delineate a possible southern margin for the caldera. Hermann (1986) further investigated the proposed southern margin of the Nogal Canyon caldera through detailed mapping northwest of the Sierra Fijardo quadrangle. He posited that part of the southern margin of the caldera is 1.6 km north of the Monticello quadrangle, where the caldera margin seems to coincide with the arcuate, southern portion of the Rock Springs fault. No additional studies have field checked the southeastern margin of the caldera within the Sierra Fijardo quadrangle, but McLemore (2012, their fig. 6) shows the southern margin as cutting through the northern section of the quadrangle north of Peñasco Peak.

METHODS

Mapping

The units described in this report and associated map were identified using both field work and analysis of aerial imagery, the latter using Stereo Analyst for ArcGIS 10.8. In the field,

locations of geologic point data were primarily obtained using a handheld GPS unit, referring to contours on a topographic map, or plotting the location using photo pairs in Stereo Analyst. We used aerial photographs that were collected by the National Agriculture Imagery Program (NAIP) in 2007–2008 and June 2022. Contacts and faults were drawn onto base maps that showed topography using contour lines and hill shading. All geologic data gathered in the field were then transferred to ArcGIS Pro 3.3.1. We relied heavily on the Stereo Analyst software to draw contacts in the southern lowlands area of the quadrangle, where unit color and elevation are effective in distinguishing between Quaternary units.

Geochemistry

Samples of unaltered to minimally altered lava were collected from 16 locations for whole-rock major and trace element analysis. Samples were processed and analyzed by ALS Geochemistry in Elko, Nevada, using inductively coupled plasma atomic emission spectroscopy (ICP-AES) for major elements and inductively coupled plasma mass spectrometry (ICP-MS) for trace elements. Samples analyzed by ICP-AES were crushed, sieved, fused, and dissolved into a solution prior to analysis. Samples analyzed by ICP-MS were crushed, sieved, fused with lithium borate flux, and dissolved in a multi-acid solution containing hydrofluoric acid.

Geochronology

Sample Processing

Samples of tuffs, lavas, and an intrusion were collected from 17 different locations in the field area for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Outcrops that were significantly altered were avoided during sampling. Sample preparation was adapted depending on the samples and datable minerals.

Samples containing sanidine were crushed and sized to 300–150 μm . These samples were treated with dilute nitric acid and hydrofluoric acid in an ultrasonic bath for 10–15 minutes, followed by three rinses with deionized water. Sanidine crystals were concentrated using heavy liquid techniques and handpicked for analysis using a binocular microscope.

Samples containing hornblende and feldspar were crushed and sized using a 28–80 mesh sieve. These samples were treated with dilute nitric acid in an ultrasonic bath to remove secondary clays or carbonate grains, followed by thorough rinsing with deionized water. Hornblende and feldspar crystals were concentrated using magnetic separation and heavy liquid techniques. Crystals were handpicked for analysis using a binocular microscope.

One sample, SFi-135-djk, required groundmass dating. This sample was crushed and sized to 600–350 μm to expose anomalous phenocrysts, which could contain excess argon. This sample was then treated with dilute nitric acid in an ultrasonic bath for 10–15 minutes to remove any secondary clays or carbonate grains, followed by three rinses with deionized water. Groundmass grains were carefully handpicked under a binocular microscope to select fragments free of phenocrysts, ensuring the isolation of uncontaminated material for accurate dating analyses.

$^{40}\text{Ar}/^{39}\text{Ar}$ Analysis

Based on their estimated ages, the samples were irradiated between 3 and 7 hours at the Oregon State University TRIGA reactor. The Fish Canyon tuff standard, with an age of 28.201 ± 0.023 Ma (Kuiper et al., 2008), was used as a neutron flux monitor. The J-value for each sample was determined by a combination of 8–10 single-grain laser fusion analyses

located in 6–8 radial positions around the irradiation disc. Correction factors for interfering neutron reactions were determined using co-irradiated CaF₂ and K-glass. Ages were calculated with a ⁴⁰K decay constant of 5.463e-10 /a (Min et al., 2000) and an ⁴⁰Ar/³⁶Ar atmospheric ratio of 295.5 ± 0.5 (Nier, 1950). Minerals and groundmass were analyzed by the incremental step-heating method using a defocused diode laser to heat the samples, and argon isotopes were measured using a ThermoFisher Scientific Helix MC multi-collector mass spectrometer. Sanidines were analyzed using the total fusion method with a 55-watt CO₂ laser, and argon isotopes were measured using an Argus VI ThermoFisher multi-collector mass spectrometer. Data reduction and age assignment are based on Pychron Software (Ross, 2019), and uncertainties are reported at the 2σ confidence level. As of the publication of this report, these ages are in progress and forthcoming. We will update the report to include the ages when we receive them.

STRATIGRAPHY AND GEOLOGIC HISTORY

Paleozoic Strata

Pennsylvanian strata on the Sierra Fijardo quadrangle consists of at least 90 m of micritic and massive limestone interbedded with laminated sandy limestone and brick-red, fine-grained sandstone. Both the micritic and sandy limestones contain fossils that include bivalves, brachiopods, and gastropods. Interbedded red sandstones are often chaotic, displaying what appears to be soft sediment deformation. Within the micritic limestone, there are sparse, boulder-sized, yellow chert nodules, which often appear brecciated with the limestone. The

dominance of limestone strata leads us to assign it to the Gray Mesa Formation (cf. Lucas et al., 2012b).

Pennsylvanian strata were deposited during a tectonically active time period. Paleozoic intraplate deformation associated with the Ancestral Rocky Mountains started in Early Pennsylvanian time and resulted in a series of topographic uplifts and adjacent basins that began accumulating transgressive-regressive sediment sequences (Ye et al., 1996).

Pennsylvanian deposition in the Sierra Fijardo quadrangle began in the Atokan (Lucas et al., 2016), following a regressive period of erosion and nondeposition during the Morrowan (Kues and Giles, 2004). A rise in sea level paired with tectonic uplift of the Pedernal and Florida highlands (to the east and west, respectively) prompted the initial phase of deposition and created a combination of an open, normal marine shelf environment and a siliciclastic-dominated marginal marine environment (Kues and Giles, 2004; Lucas et al., 2012a). In the vicinity of the mapping area, this time period produced offshore marine shales and deeper shelf carbonates of the Red House Formation, which is mapped to the west (Lucas et al., 2012a; Koning et al., 2014). During the Desmoinesian, a transgressive maximum contributed to widespread basin subsidence and deposition of shelf carbonate facies across what is now New Mexico. These shelf carbonates generally manifest as massive, cliff-forming, gray, cherty limestone and are referred to as the Gray Mesa Formation (formerly the Nakaye Formation) in the vicinity of the map area, such as in the Monticello quadrangle to the west (Lucas et al., 2012b; Koning et al., 2014). Following a period of relative tectonic quiescence during the Desmoinesian, the Missourian marked a period of renewed tectonic uplift in both the Pedernal and San Luis-Uncompahgre highlands (Kues and Giles, 2004). The increasing proportion of

terrestrial, siliciclastic sediments eroding from these highlands resulted in the deposition of nonmarine red shales interbedded with open-marine shelf carbonates and is recognized as the Bar B Formation (Lucas et al., 2016). Of these Pennsylvanian strata, only the Gray Mesa Formation is exposed in the map area.

Lucas et al. (2016) suggest that differential local subsidence and/or syndepositional tectonism caused the Pennsylvanian section near Mud Spring Mountain to be thicker than the section in the Fra Cristobal-Caballo Mountains. In particular, the Bar B Formation near Mud Springs Mountain is twice as thick as in the Fra Cristobal-Caballo Mountains. Lucas et al. (2016) propose that this difference in Bar B Formation thickness, among other things, complicates previous interpretations of glacio-eustatic cyclicity within the formation (Soreghan, 1994). Lucas et al. (2016) point out that while there may be some component of glacio-eustatic forcing that is recorded in the Mud Springs Mountain section, those same cycles were not recorded equally across south-central New Mexico. As such, local subsidence and tectonics, not glacio-eustatic forcing, likely acted as the primary driver of apparent sedimentary cycles during this time period.

The Abo Formation was deposited during the Wolfcampian (Kues and Giles, 2004; Lucas et al., 2012c). At this time, tectonism associated with the Ancestral Rocky Mountains was waning (Kues and Giles, 2004). The Abo mostly consists of reddish-brown, fine-grained floodplain deposits that are not exposed in the map area, but the decimeter-scale, ledge-forming, very fine-grained sandstones that are exposed indicate crevasse splays or broad channel fills associated with paleorivers flowing toward the southeast (Seager and Mack, 2003).

Paleogene to Neogene System: Volcanic Rocks

From the Late Cretaceous through the Paleogene, tectonic uplift and erosion associated with the Laramide orogeny removed the Mesozoic strata in the mapping area and produced hilly paleotopography in the region. Extensive caldera building and volcanism across the southwestern portion of the state began in the late Eocene and continued through the earliest Miocene. A complex interfingering of pyroclastic density currents, lavas, ash falls, and volcanoclastic sediments now blankets the region, thickening where deposits filled paleovalleys that were formed during Laramide deformation or localized erosion during volcanism (Fig. 2).

The Paleogene-Neogene stratigraphy of the map area is complex due to variable exposures on different fault blocks; the most complete section is found on Rimrock Ridge in the east-central quadrangle (Fig. 3), but not all units are exposed there. We describe the volcanic and volcanoclastic succession from bottom to top. The lowest map units are dacites and trachydacites of the Red Rock Ranch Formation (Farkas, 1969), which sit unconformably on top of limestones of the Gray Mesa Formation and are interbedded with volcanoclastic debris flows of the lower Spears Group (*sensu* Cather et al., 1994). The lowest lavas consist of (1) a light-gray lava with 10–15% plagioclase phenocrysts commonly 5 mm long (Fig. 4) and containing 5–13% hornblende and biotite, and (2) a younger, light-gray, equigranular lava with 8–15% phenocrysts of hornblende in a plagioclase-rich groundmass (Fig. 5; all phenocryst percentages reported are based on surface area). Both units, which range in age from 41 to 39 Ma, also commonly display flow banding and commonly underlie thick, dome-like ridges in the center of the quadrangle. It is possible that these lavas are locally sourced from a dome complex within the mapping area, but considerable faulting and erosion make that interpretation challenging

to confirm. Above these dacites is a commonly vesicular trachyandesite flow, which has 10–15% (total) phenocrysts of pyroxene, plagioclase, and hornblende (Fig. 6). This trachyandesite is likely correlative with the Red Rock Arroyo andesite, which is mapped on the Monticello quadrangle and to the northwest of the map area (Farkas, 1969; Koning et al., 2014).

Overlying and commonly interfingering with these lava flows are whitish to light-gray, volcanoclastic conglomerates and sandstones of the lower Spears Group. Conglomerate intervals contain pebble- to boulder-sized andesite-dacite lava and tuff clasts in a fine- to medium-grained, ashy sand matrix. Sandstone intervals are fine- to coarse-grained. The poorly sorted nature of the sediment and lack of sedimentary structures (massive) indicate deposition primarily by debris flows and/or lahars.

The first pyroclastic density flow deposited and preserved in the map area is the tuff of Aragon Draw at 36.11 ± 0.03 Ma (Koning et al., 2014), which is well exposed on the western edge of the quadrangle. The tuff of Aragon Draw varies in color from red to brown and commonly preserves a thin package of volcanoclastic sediments between its flows. The phenocryst assemblage includes 1–15% sanidine phenocrysts (commonly chalky and altered) and trace biotite. Both the red and brown varieties of the tuff typically have a high concentration of lithic fragments (up to 35%) and rheomorphic textures (Fig. 7), which suggests a fairly local source, although a source caldera has not yet been identified. On the east side of the quadrangle, exposures of the tuff of Aragon Draw are limited and appear to be filling paleochannels in the vicinity of Peñasco Spring.

The tuff of Aragon Draw was followed by deposition of the voluminous Luna Park Tuff at about 35.76 to 35.70 Ma (Koning et al., 2014; this study). The Luna Park Tuff is a light-brown to pink, crystal-rich, lithic-rich tuff (Fig. 8). This tuff contains 15–30% sanidine, 2–3% pyroxene, less than 3% biotite, about 10% fiamme, and 5–30% lithics up to 30 cm long. In the eastern part of the map area, the Luna Park Tuff grades upsection to a lighter color, is less welded, and contains up to 5% copper-colored biotite. The source caldera of the Luna Park Tuff is unknown, but the high concentration of large (up to 30 cm) lithic fragments suggests a nearby source cauldron that has been obscured by later volcanism and faulting.

Following deposition of the Luna Park Tuff, light-brown to white volcanoclastic sediments and reworked tephra of the middle Spears Group were deposited (Fig. 9). These sediments are in tabular beds typically 0.5–1.0 m thick, and the sand is mainly medium- to coarse-grained. Conglomeratic intervals contain intermediate-composition lithic clasts up to 35 cm long. This package of sediment thickens to the east and is often absent in the west, suggesting a post-Luna Park Tuff paleoslope dipping to the east.

At about 35.4 Ma (Cather et al., 2024; this study), the Datil Well Tuff was deposited discontinuously on top of either the middle Spears Group or the Luna Park Tuff. The Datil Well Tuff is strongly welded, crystal-rich, and reddish-brown to maroon. It has 25–30% phenocrysts of sanidine and lesser biotite. Upsection, the tuff has 5–15% phenocrysts and is less welded, and lithic fragments increase to 3–7% (Fig. 10). The source cauldron for the Datil Well Tuff is unknown, but it likely lies to the northwest near Datil, New Mexico (McIntosh et al., 1992).

After a relatively long period of nondeposition and/or erosion in the map area, a relatively crystal-poor ash-flow tuff, which we infer to be the La Jencia Tuff, was deposited directly on the Datil Well Tuff or Luna Park Tuff at 29 Ma (Cather et al., 2024; this study). This crystal-poor ash-flow tuff is thin (<30 m) and lithic-poor where mapped (Fig. 11). Its color ranges from light-orange to reddish-brown to gray, and it contains up to 8% lithic fragments. The tuff is strongly welded and has 5–10% fiamme and 3–10% phenocrysts of sanidine. Brecciation of the tuff is common on the west side of the quadrangle.

Shortly after the emplacement of this crystal-poor La Jencia Tuff, the La Jara Peak basaltic andesite flowed across the northwestern section of the map area. The La Jara Peak basaltic andesite is aphanitic, commonly vesicular, and commonly altered within the map area (Fig. 12).

The most voluminous ignimbrite on the Sierra Fijardo quadrangle is the Vicks Peak Tuff, which erupted from the Nogal Canyon caldera at about 28.8 Ma (Ferguson et al., 2012; Cather et al., 2024; this study). The Vicks Peak Tuff is gray, crystal-poor, and lithic-poor in the map area (Fig. 13). It is commonly strongly foliated with a strong eutaxitic texture, has 0.5% sanidine phenocrysts, and commonly has spherulites 2–4 cm in diameter. Due to the map area's proximity to the Nogal Canyon cauldron, the Vicks Peak Tuff is more than 180 m thick and dominates the Cenozoic volcanic cover in the northern portion of the Sierra Fijardo quadrangle.

Volcaniclastic sediments of the upper Spears Group were deposited on top of the Vicks Peak Tuff, filling in discontinuous paleotopographic lows. These upper Spears Group sediments vary from fine-grained to conglomeratic with abundant subangular clasts dominated by Vicks

Peak Tuff (Fig. 14). At the southern border of the map area, a matrix-supported, very poorly sorted conglomerate containing abundant clasts of Vicks Peak Tuff unconformably overlies Luna Park Tuff (?). We interpret this to be a subunit of the upper Spears group and correlative to the Seferino Hill conglomerate of the Monticello quadrangle (Koning et al., 2014). We also note that Koning et al. (2014) misinterpreted the Seferino Hill conglomerate as older than it likely is based on its clasts.

In the northern section of the map area, a localized eruption emplaced a viscous, strongly flow-banded rhyolite (Fig. 15C). The base of the flow is glassy and fragmental, indicating that it may have interacted with wet sediments at its base (Figs. 15A and 15B). Possibly contemporaneous with the eruption of this rhyolite flow is the emplacement of a highly localized, crystal-rich, quartz-bearing tuff (Fig. 16). Just north of Peñasco Peak, this local tuff caps sediments of the upper Spears Group and is overlain by a rhyolite flow. We tentatively correlate the local tuff north of Peñasco Peak to a quartz-bearing tuff observed at the northern border of the map area near Deer Springs Canyon. However, the northern tuff appears to be interbedded with pulses of Vicks Peak Tuff and so may be unrelated to the local tuff near Peñasco Peak.

Finally, a series of rhyolite domes/stocks were emplaced in the vicinity of Peñasco Peak and Ducknest Tank at about 28.5 to 28.4 Ma (this study). These intrusions often exhibit flow banding (Fig. 17) and intrude into the upper Spears Group sediments overlying the Vicks Peak Tuff. The Vicks Peak Tuff is typically altered and/or brecciated in the vicinity of these rhyolite intrusions (Figs. 18 and 19), suggesting that their subsurface plumbing system may have

mobilized hydrothermal fluids, causing brecciation of the Vicks Peak Tuff. Alternatively, this secondary alteration may be related to Rio Grande rifting in the Miocene.

Neogene to Quaternary System: Basin Fill

The southern portion of the quadrangle is in the western Engle basin and is near the right step-over between the northern Palomas basin and central Engle basin. Both are half grabens tilted to the east, with the northern Palomas half graben tilted against the Mud Springs fault and the northern Willow Draw fault, and the Engle basin tilted eastward along the Walnut Canyon fault (Chapin 1971; Lozinsky, 1987). Deposition in the map area probably began by at least Pliocene time as ancestral Rio Grande tributaries transported piedmont alluvium from the San Mateo Mountains and Sierra Cuchillo to the western portion of the Engle basin.

The Rio Grande and its tributaries overall aggraded from about 5 to about 0.8 Ma (Mack et al., 2006), depositing sand and gravel of the Palomas Formation, which is the local upper formation-rank unit of the Santa Fe Group (Lozinsky and Hawley, 1986). The Palomas Formation may extend downsection to the upper Miocene, as it does near Elephant Butte (Koning et al., 2025), but only the uppermost strata of the Palomas Formation are exposed in the map area. The upper Palomas Formation is sandy-gravel to gravelly-sand with common paleosols (Fig. 20). Strata are in medium to thick, tabular to broadly lenticular beds. Gravel clasts are commonly imbricated and clast- to sand-supported and were deposited by ephemeral streams that have drainage basins that largely coincide with modern drainages. Paleosols commonly exhibit a reddish-brown to orangish Bw or Bt horizon overlying a calcic horizon having a Stage I to III carbonate morphology.

Widespread aggradation of the Palomas Formation ceased at around 0.8 Ma and transitioned into overall incision punctuated by occasional periods of stability. One of the most prominent stable surfaces in the map area is the Cuchillo surface, which previously has been thought to represent the highest aggradational surface of the Santa Fe Group prior to Rio Grande incision at 0.8 Ma (Fig. 21; Lozinsky and Hawley, 1986; Mack et al., 2006; McCraw and Love, 2012), an interpretation that we counter (see below). This surface slopes gently to the east (1°) and is relatively flat or consists of concordant, low ridges separated by broad, shallow drainages. This surface has either a light-gray color in aerial photos where slight paleotopographic highs are eroding, or the surface has a reddish color where it tends to have one or more of these features: (1) varnishing of exposed surface clasts commonly found on moderately to well-developed desert pavements, (2) overturned surface clasts with reddened undersides, (3) Bw or Bt soil horizon(s), or (4) slope wash/sheetwash that reworked nearby Bw or Bt soil horizons (Fig. 21). These two colors, as seen in aerial imagery, form the basis of subdividing the Cuchillo surface into two components: a reddish unit (Qcsr) and a light-gray unit (Qcslg).

Near the western quadrangle boundary, south of County Road 34, there is an older surface that rises 7–9 m above the Cuchillo surface. This surface is notable in aerial imagery due to its gray color and dissected appearance (Fig. 21). We refer to this higher surface as the Aragon surface (slightly modifying terminology from McCraw and Love, 2012, their fig. 6). We interpret that the Aragon surface is close to the maximum aggradation of the Santa Fe Group in the proximal piedmont, here and probably in the northern part of the Monticello quadrangle. In these areas, the Cuchillo surface probably represents a planation of the Aragon surface, with

several meters of erosion. This erosion may not have notably affected the middle to distal parts of the Cuchillo surface in the Engle and Palomas basins.

Near the eastern border of the northeastern corner of the quadrangle, near San Jose Arroyo and Carbon Canyon, there are two geomorphic surfaces that may correlate to the aforementioned red surface component of the Cuchillo surface and the higher, grayer Aragon surface. However, we choose not to extend these formal names into this area until further mapping is completed in the southwestern part of the San Marcial basin. On the map, we provide provisional names for two overlays depicting these surfaces: (1) gray, higher geomorphic surface in the northeastern quadrangle, and (2) red, lower geomorphic surface in the northeastern quadrangle. These two surfaces are commonly separated by about 5–8 vertical meters, although locally it is less.

Also during the Quaternary, a series of small rift-related basalts erupted across the Engle basin. A small outcrop of basanite near the eastern border of the quadrangle (geochemistry suggests either basanite or tephrite composition) represents this Quaternary volcanism. Basaltic eruptive centers and flows become more abundant to the southeast of the Sierra Fijardo quadrangle in the southern Engle basin and Cutter sag (Lozinsky, 1987; Cikoski et al., 2017; Cikoski, 2018).

DISCUSSION

Structure

Four large-scale fault structures surround Peñasco Peak and are named in this report (Fig. 22). To the north of Peñasco Peak, a system of approximately north-south-striking faults

(striking 340° to 050°), hereafter referred to as the Los Pillares fault zone (after the Los Pillares well), locally juxtaposes Vicks Peak Tuff against volcanoclastic sedimentary rocks. East-west-striking faults to the south and west of Peñasco Peak are named according to their location relative to Peñasco Peak, and are differentiated by their deformation style (discrete and diffuse, respectively). We interpret that the two east-west-striking faults may be indirectly related to the collapse of the Nogal Canyon caldera, which formed northwest of the map area during the eruption of Vicks Peak Tuff. Stratigraphic relations also suggest two northwest-striking, buried faults south of Peñasco Peak, which we do not name in this report.

Los Pillares Fault Zone

The surface exposure of the Los Pillares fault zone is around 5 km long and is mapped from Eagles Roost to the northern border of the map area. The fault zone forms an arcuate map pattern, striking northwest at its northern end and northeast at its southern end. At its southern end, the Los Pillares fault zone splays into a northeast-trending graben with a down-dropped block that contains a sequence of post-Vicks Peak strata: upper Spears Group, a local quartz-bearing tuff, and rhyolite flow. North of the graben, Vicks Peak Tuff is exposed on both the hanging wall and footwall of the Los Pillares fault zone. The Vicks Peak Tuff lacks stratigraphic datums, but higher topography on the footwall suggests about 100 m of west-down throw. The fault zone primarily accommodates west-down, normal displacement, but slickenline measurements (rake of 60° toward 303°) on the northern end of the fault (UTM coordinates 284727 m E, 3707807 m N) indicate there has been right-lateral oblique slip, which is also consistent with the change in strike and presence of a graben at the southern end of the fault system. The orientation and displacement of the Los Pillares fault zone are consistent with

east-west extension during Rio Grande rifting; the movement would postdate the Vicks Peak Tuff.

South Peñasco Peak Fault

The surface exposure of the South Peñasco Peak fault is about 7 km long, juxtaposes Eocene Red Rock Ranch Formation against late Oligocene tuffs, and strikes northeast but contains an east-west-striking central segment (Fig. 23). At its western end, the steeply dipping fault plane preserves slickenline measurements that indicate northwest-down, left-lateral oblique fault slip (UTM coordinates 282812 m E, 3703288 m N). Similar kinematic indicators are not preserved at the eastern end of the South Peñasco Peak fault, but an increase in fault splays just east of Peñasco Peak (UTM coordinates 285866 m E, 3704434 m N) is consistent with a releasing bend caused by continued left-lateral oblique displacement. Based on reconstructions of Vicks Peak Tuff offset, we interpret a stratigraphic displacement of around 270 m.

West Peñasco Peak Fault Zone

The West Peñasco Peak fault zone is a 1- to 2-km-long, diffuse zone of brittle deformation with an overall northwest strike. The zone contains short (hundreds of meters long) faults striking in two approximately orthogonal orientations, 020° and 300°, with stratigraphic throw that ranges from 50 to 150 m. Most of the northwest-striking faults indicate north-down slip based on stratigraphic relationships, but accurate fault interpretations are complicated by paleotopographic effects and limited fault exposures. Mapping in the Monticello quadrangle to the west (Koning et al., 2014) suggests that displacement on the West Peñasco Peak fault zone may decrease to less than 20 m at the quadrangle boundary.

The eastern extent of the West Peñasco Peak fault zone terminates into a north-striking, steeply west-dipping fault at Lumber Canyon. In the footwall of the north-striking fault, there is a discrete west-striking fault with similar kinematics to the West Peñasco Peak fault zone, suggesting a genetic relationship. If this west-striking fault is related to the West Peñasco Peak fault zone, it would imply that the north-striking fault in Lumber Canyon is younger, which constrains the timing of the West Peñasco Peak fault zone.

Buried Faults

The easternmost buried fault is located 1.6 km west of Peñasco Spring, strikes about 315°, and truncates Pennsylvanian Gray Mesa Formation. Fault orientation and kinematics are not well constrained for this fault. We interpret an east-down throw of about 65 m for this fault using the cross-section A–A'.

The location of the westernmost buried fault is poorly constrained, but it is located near Flying X Ranch and Lumber Canyon. The east-dipping Permian Abo Formation exposed 3 km south of Flying X Ranch contrasts the east-dipping Pennsylvanian Gray Mesa Formation exposed farther to the east, a relationship that is best explained by a northwest-striking fault. Fault orientation and kinematics are not constrained for this fault. We interpret a stratigraphic throw of about 1.2 km for this fault using cross section A–A'.

Geochemistry Summary

The analyzed samples vary in major element geochemistry, with SiO₂ concentrations varying from 45.8 to 78 wt%. Appendix 1 contains a table of whole-rock geochemical data. Using the Le Maitre et al. (2002) classification diagram, most samples straddle trachydacite-dacite-trachyandesite-andesite compositions (Fig. 24). All samples, except the three most mafic samples, are subalkaline (Fig. 25A), and all intermediate-composition samples are considered “high-K” by the definition of Gill (1981; Fig. 25B).

Trace element geochemistry is fairly uniform between the plagioclase-phyric dacite (PERdp) and the hornblende-plagioclase dacite (PERd) of the Red Rock Ranch Formation, with notable enrichments of Ba and K by two orders of magnitude relative to primitive mantle (Sun and McDonough, 1989; Fig. 26). Unit PERdp shows overall self-consistent trace geochemistry, with inter-sample variability becoming more pronounced only in Lu (0.12–0.17 ppm). Unit PERd shows more variability among samples, particularly in Cs (0.35–0.83 ppm), Cr (19–43 ppm), Lu (0.19–0.30 ppm), Sc (5.5–8.3 ppm), Ta (0.3–0.5 ppm), and V (48–88 ppm) concentrations. The most notable difference between PERdp and PERd trace geochemistry is the systematic enrichment in heavy rare earth elements (HREEs; Dy to Lu) shown in PERd relative to PERdp. The aphyric trachyandesite unit (PERta) shows similar trace geochemistry to unit PERdp, with only a slight enrichment in HREEs relative to PERdp.

The high-silica rhyolite intrusion (PEir) shows enrichment of Cs, Rb, Th, U, and K, all of which have concentrations that are two orders of magnitude higher than primitive mantle (Fig. 26). Unit PEir also shows depletion of P and Ti relative to primitive mantle. Unit PEir has the highest concentration of HREEs relative to all other samples analyzed in this study.

The pyroxene-plagioclase trachyandesite unit (PErt) is enriched in Cs, Rb, Ba, Th, U, and K by two orders of magnitude relative to primitive mantle (Fig. 26). The basaltic andesite unit (PErb) is enriched in Ba by two orders of magnitude relative to primitive mantle and is enriched in Sr relative to all other samples analyzed here (Fig. 26). The Quaternary basanite unit (Qb) is most enriched in Nb, P, Ti, Gd, and Eu relative to other analyzed samples, and has the second-highest Ta concentration behind unit PEir (Fig. 26).

Geochronology Summary

We report 18 new geochronologic dates for 17 different samples collected in the map area. See Appendix 2 for full tables and figures of these results.

The oldest rocks dated in the map area are dacites from the Red Rock Ranch Formation (units PErdp and PErd). Plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ dates for unit PErdp range from 39.98 ± 0.14 to 40.10 ± 0.15 Ma, whereas hornblende and plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ dates for unit PErd range from 39.12 ± 0.16 to 40.99 ± 0.12 Ma. The relatively wide range of dates for each of these units is likely a function of the material that was dated, as plagioclase commonly contains excess or inherited Ar. In general, the spread of dates for each unit is not statistically significant, and we are comfortable in our assignment of these samples to their respective units. Additionally, although there is some overlap in dates between units PErd and PErdp, stratigraphic observations in the field suggest that unit PErd is slightly younger than unit PErdp. Given the extent of the overlap in dates, it is likely that unit PErd erupted within about a million years of unit PErdp.

Ignimbrites in the map area were dated using sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ and each date is consistent with previously published dates. The oldest ignimbrite in the map area is the Luna Park Tuff, which is between 35.76 ± 0.03 and 35.72 ± 0.02 Ma; the Datil Well Tuff is 35.41 ± 0.02 Ma; the La Jencia Tuff is between 29.02 ± 0.02 and 29.00 ± 0.03 Ma; the youngest ignimbrite is the Vicks Peak Tuff at 28.80 ± 0.03 Ma. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ dates for the rhyolite intrusion (unit PEir) range from 28.36 ± 0.02 to 28.46 ± 0.04 Ma. The youngest volcanic unit in the map area is unit Qb at 2.51 ± 0.03 Ma, which further supports its connection to Rio Grande rift volcanism.

Both the date and the lithologic characteristics of the Datil Well Tuff in this map area are consistent with mapping in the Quebradas region east of the Bustos fault (Cather et al., 2024; p. 103). Additionally, the lithologic characteristics and dates of the Luna Park Tuff in this map area are consistent with mapping on the Monticello 7.5-minute quadrangle (Koning et al., 2013). These aspects of the Luna Park Tuff are also strikingly similar to the tuff of Rocque Ramos Canyon, which was mapped on the Black Hill 7.5-minute quadrangle and yielded dates of 35.72 ± 0.01 and 35.75 ± 0.01 Ma (Jochems and Koning, 2019); this similarity may suggest that the Luna Park Tuff and tuff of Rocque Ramos Canyon are correlative.

A plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ date of 36.13 ± 0.34 Ma is reported for the middle Spears Group (unit PEsm), on what was thought to be a primary ash layer; however, we do not display this date on the map sheet. Based on stratigraphic relationships, we interpret this date to reflect older, reworked material rather than a true depositional age for the unit. Instead, high precision sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ dates from the ignimbrites that stratigraphically bracket this sediment (units PEIpt and PEdwt) suggest that unit PEsm was deposited between 35.72 ± 0.02 and 35.41 ± 0.02 Ma.

Rhyolite Intrusion

The margins of the rhyolite domes (PEir) that make up Peñasco Peak and Eagles Roost display textures formed during emplacement into the surrounding country rock. East of Peñasco Peak, the dome has partially melted the volcanoclastic sediments of the upper Spears Group where they are in contact with the rhyolite. In this area, the margin of the rhyolite dome also contains pebble- to boulder-sized xenoliths, including compositions of both the adjacent country rock and rocks that are not obviously exposed in the map area. At the top of Peñasco Peak, unit PEir contains abundant pebble-sized xenoliths of Vicks Peak Tuff. These relations indicate that PEir postdates both the Vicks Peak Tuff and upper Spears Group, consistent with the Ar dates obtained during this investigation.

On the west side of the rhyolite dome, south of Ducknest Tank, there are distinctive textures associated with smaller offshooting “dikelets” of the rhyolite dome. There are three consistent zones preserved at the rhyolite/country rock contact of the dikelets (Fig. 18). The first zone, at the margin of the dikelet, is characterized by fine-grained and glassy rhyolite, as compared with the usually porphyritic main body of the rhyolite dome. The next zone, moving outward from the dikelet margin, is highly silicified and contains abundant polymict, pebble-sized, angular rock fragments. This silicified, fragmental zone does not appear to fully belong to either the rhyolite or the country rock. The final zone consists of country rock, typically Vicks Peak Tuff, but displays a tight, brittle, “crackle-style” breccia with no visible matrix aside from drusy stilbite mineralization (Fig. 19).

Brecciation adjacent to rhyolite domes is also reported by Foruria (1984) in the Monticello quadrangle to the west. In his report, Foruria (1984) notes a vertical contact between the rhyolites at Aragon Hill and an “intrusive breccia” that hosts economic minerals.

Alteration in Vicks Peak Tuff

We identified three different styles of alteration in Vicks Peak Tuff that are primarily mapped in the hanging wall of the Los Pillares fault zone. The first is a white, punky, kaolinized alteration, which we have mapped as unit PEvptw (Fig. 27). In outcrop, unit PEvptw locally preserves the internal foliation structures and distinctive lineations of PEvpt but preserves few recognizable minerals. The texture is often rough and friable. The next alteration product is brown to dark-brown and very hard (often making a “pingy” noise when struck by a rock hammer and easily scratching a rock hammer), which we have mapped as unit PEvpts (Fig. 28). Unit PEvpts is silicified, commonly does not preserve Vicks Peak Tuff foliation and spherulites, and forms tall, rounded pillars throughout the northern portion of the map area. The third alteration style is an angular, tight breccia, which commonly has a coating of chalcedony, or occasionally zeolite (stilbite), mineralization (Fig. 19); we map this alteration style as PEvptb. Unit PEvptb is commonly observed adjacent to and interacting with the rhyolite intrusion. However, this breccia is also observed throughout the northern portion of the map area, where it is sometimes associated with fault structures.

It is possible that all of these alteration products are related to the post-Vicks Peak Tuff rhyolite intrusions, which are locally exposed in both this map area and the Monticello quadrangle to the west. If so, then the geometry of these intrusions is more extensive in the

subsurface and is likely altering the overlying Vicks Peak Tuff through contact heating and hydrothermal effects. In particular, these hydrothermal fluids may have been pressurized enough to create the shattering effect observed in unit PEvptb.

In the northwestern portion of the quadrangle, we identified a discontinuous rhyolite flow (Fig. 15) deposited on top of Vicks Peak Tuff, likely filling a paleotopographic low. In the vicinity of this flow, we observed all styles of alteration, with brecciation and kaolinization occurring closest to the rhyolite flow and silicification occurring within a kilometer of the flow. We posit that a vent associated with this rhyolite flow may be nearby, but it has not been preserved. Therefore, this alteration strongly suggests the presence of a shallow subsurface magmatic source for the rhyolite flow.

Foruria (1984) identified and mapped extensive argillic alteration of Vicks Peak Tuff to the west and northwest of the Sierra Fijardo quadrangle. He posits that this argillic alteration occurred after the Springtime Canyon quartz latite flow (possibly correlative with the rhyolite flow mapped in this study) was deposited, and that hydrothermal fluids moving through the Vicks Peak Tuff were unable to rise vertically through the rhyolite flow and instead focused the alteration to the upper portion of the Vicks Peak Tuff. While we observed this white, kaolinized, argillic alteration below the rhyolite flow on the Sierra Fijardo quadrangle, we did not observe rhyolite near the other exposures of argillic Vicks Peak Tuff. It is possible that rhyolite flows overlying those occurrences were not preserved, but it may be that argillic alteration in the Sierra Fijardo quadrangle is the result of an additional mechanism, such as rhyolitic vents or shallow intrusions that are not exposed at the surface.

Variations in Local Stratigraphy and Paleotopographic Effects

Within the map area, Rimrock Ridge represents the most complete stratigraphic section and is generally unperturbed by faulting; however, the stratigraphy at Rimrock Ridge is not indicative of the stratigraphy of other places in the map area. Notably, there are four major variations in stratigraphy from east to west (Fig. 2). The first of these is the difference in the Red Rock Ranch Formation. Beneath the tuff of Aragon Draw on the west side of the quadrangle, the Red Rock Ranch Formation is primarily thick, flow-brecciated, intermediate-composition lava flows. While there are flow-brecciated andesites on the east side of the map area, they are thin, discontinuous, and interbedded with thick volcanoclastic sediments of the lower Spears Group.

The second variation is in the Datil Well Tuff and the middle Spears Group sediments. At Rimrock Ridge, Datil Well Tuff overlies the middle Spears Group sediments, which are above the Luna Park Tuff. Toward the west, just south of Ducknest Tank, the middle Spears Group pinches out and the Datil Well Tuff becomes nearly twice as thick as it was on the east side of the map area. However, farther to the west, neither the Datil Well Tuff nor the middle Spears Group is preserved. On the west side of the map area, La Jencia Tuff sits directly on Luna Park Tuff. This variation is likely due to post-Luna Park Tuff paleotopography.

The third variation is that the regional Hells Mesa Tuff is preserved in small, discontinuous outcrops on the west side of the quadrangle, above the Luna Park Tuff. Hells Mesa Tuff was not observed anywhere else in the map area, so these exposures likely represent

the southernmost extent of the tuff, which erupted from the Socorro cauldron (McIntosh et al., 1992).

The fourth major stratigraphic variation is that of the La Jara Peak basaltic andesite. This basaltic andesite is present throughout the map area, except on Rimrock Ridge. The thickness of this unit varies widely within the map area (from about 5 to 35 m), even over short distances. This rapid variation is likely partially due to paleotopographic effects, but it may have also been caused by local scouring during the emplacement of the Vicks Peak Tuff.

One of the most significant paleotopographic features that we observed in the field is on the west side of the quadrangle where Vicks Peak Tuff appears to cascade down into an apparent paleovalley and is deposited directly on Red Rock Ranch Formation. Although this area is also highly faulted, we interpret this particular contact as an unconformable contact resulting from pre-Vicks Peak Tuff erosion (near UTM 280814 m E, 3704168 m N).

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FIGURE CAPTIONS

Figure 1—Map showing geographic features (black labels) and informal physiographic provinces (red dividing line and labels) of the Sierra Fijardo quadrangle. Interstate 25 (thick red line) trends northeast through the southeastern corner of the map area. Light-gray lines are county and U.S. Forest Service roads. Pale-blue lines are streams (names in blue text).

Figure 2—Composite schematic illustration of Paleogene volcanic stratigraphic relationships. Note that horizontal and vertical axes are not to scale, and all faulting has been omitted. Vertical text labels at the top of the figure refer to the approximate location of geographic markers in the map area.

Figure 3—Annotated photograph looking east from Peñasco Peak showing the sequence of regional tuffs, sediments, and older lavas that is typical in the map area. Note that the tuff of Aragon Draw is discontinuous and appears to fill paleotopography.

Figure 4—Photograph of the plagioclase-phyric dacite unit (PERdp) of the Red Rock Ranch Formation. Large (~5 mm), altered plagioclase phenocrysts are diagnostic of the unit. Unit PERdp is the basal unit of the Red Rock Ranch Formation and is often deposited directly on limestone of the Gray Mesa Formation.

Figure 5—Photograph of the hornblende-plagioclase dacite unit (PERd) of the Red Rock Ranch Formation. Unit PERd varies from equigranular to porphyritic and is locally separated from unit PERdp by a red-tinged volcanoclastic sediment (unit PEsIr).

Figure 6—Photograph of the trachyandesite unit (PErt) of the Red Rock Ranch Formation. Unit PErt is reddish in color, contains plagioclase and pyroxene phenocrysts, and is commonly vesicular. Unit is correlative to the Red Rock Arroyo andesite of Koning et al. (2014).

Figure 7—Photographs of two different varieties of the tuff of Aragon Draw (PEtad). (A) The red, crystal-poor, highly rheomorphic variety of unit PEtad on the west side of the quadrangle. (B) The brown variety of unit PEtad, which is common near Peñasco Spring. The brown variety varies from lithic-rich to lithic-poor and typically has cloudy sanidine phenocrysts.

Figure 8—Photograph of the lithic-rich, weakly welded Luna Park Tuff (PElpt). Hammer handle is ~4 cm wide. Note the abundant clasts of Red Rock Ranch Formation lithics.

Figure 9—Photograph of the middle Spears Group sediments (unit PEsm) on the east side of Rimrock Ridge. Beds are ~45 cm thick at the geologist's eye level.

Figure 10—Photograph of a hand sample of the Datil Well Tuff (unit PEdwt). Unit is very strongly welded, and red fiamme are abundant. Photo taken south of Ducknest Tank.

Figure 11—Photograph of a hand sample of the unit interpreted as La Jencia Tuff (PEljt). Unit is crystal-poor and strongly welded. The pumice is commonly devitrified.

Figure 12—Photograph of a hand sample of the La Jara Peak basaltic andesite (unit PEljp) from a location south of Ducknest Tank. Unit is commonly aphanitic and vesicular. Note the mineralization coating the vesicles. Fingernail is ~1 cm long.

Figure 13—Photograph of an outcrop of Vicks Peak Tuff (unit PEvpt). Note the lineations (oriented horizontally in the photo) on the foliation plane. Photo from the NW corner of map area. Hammer handle is ~20 cm long.

Figure 14—Photographs of outcrops of the upper Spears Group sediments (unit PEsu). Unit PEsu varies from sandstone to conglomerate. Clasts are primarily Vicks Peak Tuff (PEvpt) composition.

Figure 15—Photographs of the rhyolite flow (unit PEr) in the northwest corner of the map area (UTM coordinates 280857 m E, 3706954 m N). (A) Photo of the fragmental base of the flow. (B) Photo of the glassy base of the flow. (C) Photo of flow banding in the upper part of the flow. Hammer is ~40 cm long, fingernail is ~1 cm.

Figure 16—Photo of the local quartz-bearing tuff PEtl (UTM coordinates 283825 m E, 3704886 m N).

Figure 17—Photograph of an outcrop of rhyolite intrusion (PEir) near the intrusion's margin. Flow foliation is very pronounced in some sections of the intrusion's margin. Individual foliation bands are ~1–5 cm thick. Hammer handle is ~30 cm long.

Figure 18—Annotated photograph of rock textures in the Vicks Peak Tuff (unit PEvpt) next to a small offshooting “dikelet” of the rhyolite intrusion (unit PEir). Hammer handle is ~30 cm long.

Figure 19—Photograph of brecciated Vicks Peak Tuff (unit PEvpt) near the rhyolite intrusion (unit PEir). Hammer handle is ~30 cm long.

Figure 20—A 15- to 20-ft-tall exposure of the Palomas Formation. There is 80% sandy gravel with 10–20% pebbly sand. Beds are very thin to thin and tabular to broadly lenticular for pebbles, but thin to thick and broadly lenticular to lenticular for cobbly sediment. Gravel consists of pebbles with 25% cobbles and 5–7% boulders composed mainly of Vicks Peak Tuff. The sand is light reddish brown to yellowish red and mostly medium- to very coarse-grained. Within the sand is an estimated 10% clay occurring as a coating on clasts. These strata are well consolidated and weakly cemented by clay.

Figure 21—Annotated Google Earth image showing the western part of the southern piedmont slope in the Sierra Fijardo quadrangle. The yellow line is the location of the topographic profile and vertically exaggerated cross section at the base of the figure. The Aragon surface (west) is underlain by light-gray, dissected terrain that projects 6–7 m above the Cuchillo surface to the east. The Cuchillo surface has two components: (1) a light-gray surface (LGS) similar to that underlying the Aragon surface but much lower and (2) a red surface (RS) component. The color of the red surface is due to (1) surface clasts that are moderately to strongly varnished, (2) Bt or Bw soil horizons immediately below the surface, (3) slope-wash or sheet flood sediment that has locally reworked Bt or Bw soil horizons, or (4) surface clasts with orangish, varnished undersides that are overturned. The reddish surface is relatively stable and flat. The light-gray surface component typically corresponds to low ridges, 0.5 to a few meters tall, that are orientated parallel to drainage flow; relatively steady erosion of these areas seemingly inhibits varnishing of clasts, soil development, and preservation of reddish slope wash. Gravelly Palomas Formation underlies both the Aragon and Cuchillo surfaces. Topographic profile

created using the ruler/path tool in Google Earth. Image is from Google Earth, © 2013 Landsat / Copernicus.

Figure 22—Schematic illustration of major faults mapped in the Sierra Fijardo quadrangle. Green lines correspond to the Los Pillares fault zone, blue lines to the West Peñasco Peak fault zone, and the purple line to the South Peñasco Peak fault. Red dotted lines are buried faults. Black lines are unnamed faults. Bolded labels correspond to the fault names. Italicized labels correspond to geographic place names and are situated in the approximate location of the referenced landmark.

Figure 23—Annotated photograph looking east-southeast from Peñasco Peak showing the approximate location of the E-W-trending South Peñasco Peak fault. “U” and “D” refer to the upthrown and downthrown sides of the mapped faults, respectively. Arrows denote the oblique movement on the South Peñasco Peak fault. Note that the La Jara Peak basaltic andesite and the La Jencia Tuff are discontinuous in this part of the map area.

Figure 24—Total alkali-silica (TAS) diagram for samples analyzed for major element whole-rock geochemistry. Sample names are abbreviated on this plot so that the prefix “24SFi-” or “SFi-” is dropped. Abbreviated sample names are color-coded based on their observed map unit name.

Figure 25—(A) Alkaline versus subalkaline classification diagram. (B) K_2O versus SiO_2 diagram after Gill (1981); samples of units Qb and PEir are not included.

Figure 26—Trace element concentrations relative to primitive mantle (Sun and McDonough, 1989) for samples analyzed for trace element whole-rock geochemistry.

Figure 27—Photographs of the white, punky, kaolinized Vicks Peak Tuff (unit PEvptw). Hammer handle is ~30 cm long.

Figure 28—Photograph of silicified Vicks Peak Tuff (unit PEvpts). Finger points to a small vein filled with chalcedony. Fingernail is ~1 cm long.

DESCRIPTION OF MAP UNITS

The units described below were mapped in the field using handheld GPS units, lidar basemaps, and aerial imagery. Stereogrammetry software (Stereo Analyst 16.6, a Hexagon Geospatial extension for ArcMap 10.8.2) helped guide accurate placement of some geologic contacts. Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. The term “clast(s)” refers to the grain size fraction greater than 2 mm in diameter. Soil horizon designations and descriptive terms follow those of Birkeland et al. (1991), Soil Survey Staff (1992), and Birkeland (1999). Stages of pedogenic calcium carbonate morphology follow those of Gile et al. (1966) and Birkeland (1999). Descriptions of sedimentary, igneous, and metamorphic rocks were based on inspection using a hand lens.

Surface characteristics and relative landscape position were used in mapping middle Pleistocene to Holocene units. Surface processes dependent on age (e.g., desert pavement development, clast varnish, calcium carbonate accumulation, and eradication of original bar-and-swale topography) were used to differentiate stream terrace, alluvial fan, and valley floor deposits. Younger deposits are generally inset below older deposits (e.g., terrace deposit suites), or they occur as a thin sheet on older deposits.

QUATERNARY

Anthropogenic Deposits

daf Disturbed ground and artificial fill (0 to 150 years old)—

Human-related excavations and fill of sand and gravel for the purpose of constructing dams and road beds. The fill is up to 10 m thick.

Hillslope and Mass Wasting Deposits

Qct Colluvium and talus deposits (Holocene and late to middle Pleistocene)—

Subangular pebble- to cobble-sized gravel blanketing steep hillslopes. There is a subordinate matrix of poorly sorted, angular to subangular, clayey-silty sand. This deposit is usually mapped below steep cliffs where thick deposits of broken rock accumulate. The unit is commonly in 5-m-wide topographic chutes. The deposit is typically unconsolidated and <8 m thick.

Qcd Colluvium with lesser debris flow deposits (Holocene and late to middle Pleistocene)—

Short

Poorly sorted, angular to subangular, clayey-silty sand and pebble- to cobble-sized gravel. Colluvium drapes the foot of relatively smooth slopes, and debris flows are inferred under small, steep fans (convex-up, bulbous landforms at the mouths of steep, low-order drainages). The proportion of colluvium is greater than the proportion of debris flows. The deposit is typically <8 m thick.

Long

Poorly sorted, angular to subangular, clayey-silty sand and pebble- to cobble-sized gravel. Colluvium drapes the foot of relatively smooth slopes, and debris flows are inferred under small, steep fans (convex-up, bulbous landforms at the mouths of steep, low-order drainages). The matrix is commonly reddish where mapped on **Fevpt**. The proportion of colluvium is greater than the proportion of debris flows. The deposit is typically <8 m thick.

Qdc Debris flow deposits with lesser colluvium (Holocene and late to middle Pleistocene)—

Poorly sorted, angular to subangular, clayey-silty sand and pebble- to cobble-sized gravel. Colluvium drapes the foot of relatively smooth slopes, and debris flows are inferred under small, steep fans (convex-up, bulbous landforms at the mouths of steep, low-order drainages). The proportion of debris flows is greater than the proportion of colluvium. The deposit is typically <8 m thick.

Qls Landslide deposit (middle Holocene to middle Pleistocene)—

Landslide deposit on the east side of Rimrock Ridge that underlies a 200-m-wide, bulbous landform below a concave-up, shallow hollow on the hillslope. Boulders and cobbles of Vicks Peak Tuff (**Evpt**) are common on the surface. The deposit likely consists of a massive to chaotic, poorly sorted mixture of gravel (pebble- to boulder-sized) with a clayey to sand matrix. The thickness of the deposit is ≈10–15 m.

Post-Santa Fe Group Alluvial Deposits

Alluvial Deposits

Qar Recent alluvium (0 to 150 years old)—

Short

Sandy gravel, pebbly sand, and sand on the lowest part of valley floors, inferred to be <150 years old and lacking topsoil development. Two geomorphic components are (1) modern channels with notable bar-and-swale topography and pebbles through boulders, and (2) low terraces ≈1 m above grade with dm-scale bar-and-swale topography and sediment dominated by sand and pebbles. The deposit is less than 3 m thick.

Long

Sandy gravel, pebbly sand, and sand on the lowest part of valley floors that is inferred to have been deposited in the last ≈150 years; note that 150 years ago roughly coincides with the termination of the Little Ice Age (Mann et al., 2002) and initiation of intensive grazing practices in the local area. Gravel consists of pebbles through boulders that are subangular (minor subrounded), poorly sorted, and composed of felsic-dominated volcanic rocks. The clast composition depends on the local source area but is typically dominated by Vicks Peak Tuff. There are two geomorphic components to the unit, both lacking noteworthy soil development. The first is modern channels exhibiting fresh-looking bars and

swales (up to 1 m tall). The sand in the channels is gray to light-gray, dominantly medium- to very coarse-grained, subrounded, poorly sorted, and composed of volcanic grains. The second geomorphic component is low terraces (≤ 1 m above the modern channel), where bar-and-swale topography is as much as a few tens of centimeters (topographic relief) and the surface is sandy and pebbly. The sediment in these low terraces is finer-grained than in the modern channels and commonly composed of sand and pebbles (minor cobbles) that are laminated to bedded (beds are generally < 30 cm thick). The sand in the second component is brown and has high amounts of fine and medium sand. The deposit is weakly consolidated and less than 3 m thick.

Qay Younger alluvium (late to middle Holocene)—

Short

Sandy gravel and gravelly sand under low terraces (< 2 m high) exhibiting thin to thick, tabular to lenticular beds. Sand is mostly brown and fine- to very coarse-grained. Topsoil generally has a Stage I+ carbonate morphology. Buried soils are characterized by Bk and Bw horizons. The surface is smooth and has a weakly developed pavement. The deposit is weakly consolidated and 2–10(?) m thick.

Long

Sandy gravel and gravelly sand underlying low terraces (< 2 m tread height). Sediment is in thin to thick, tabular to lenticular beds. Gravels are clast- to sand-supported, subangular, and poorly sorted and consist of pebbles, lesser cobbles, and $< 5\%$ boulders composed of felsic-dominated volcanic rocks (mostly **R₁vpt**). The sand is brown, fine- to very coarse-grained, subangular to subrounded, poorly sorted, and mostly composed of volcanic grains. Sand beds commonly have scattered pebbles. Less than 20% of observed beds are composed of silty-clayey very fine- to fine-grained sand (locally with scattered pebbles). Topsoil generally has a Stage I+ carbonate morphology, locally with an overlying Bw horizon. Buried soils are also characterized by calcic horizons (Stage I to I+ and up to 30 cm thick), locally overlain

by a 10- to 20-cm-thick Bw horizon. The geomorphic surface is smooth and has a weakly developed desert pavement (barely noticeable varnishing, no to very weakly developed Av peds, and moderate to high clast density). **Qay** alluvium extends horizontally under a disconformity at the base of **Qar** and extends vertically downward to bedrock or the Palomas Formation. The deposit is weakly consolidated and probably 2–10(?) m thick.

Qary Recent and younger alluvium (0 years old to middle Holocene)—

Recent alluvium (**Qar**) and subordinate younger alluvium (**Qay**); see detailed unit descriptions above. The deposit is 1–10(?) m thick.

Qayr Younger and recent alluvium (0 years old to middle Holocene)—

Younger alluvium (**Qay**) and subordinate recent alluvium (**Qar**); see detailed unit descriptions above. The deposit is 1–10(?) m thick.

Piedmont-terrace Deposits

Qai Intermediate alluvium (middle Holocene to late Pleistocene)—

Short

An allostratigraphic deposit above **Qay** and below **Qao**. A coarse and fine lithofacies are recognized and lack calcic soil horizons with greater than Stage II morphology. The coarse lithofacies is sandy gravel and gravelly sand, and the fine lithofacies is clayey-silty very fine to fine sand. The 1- to 4-m-thick deposit has a smooth, weakly to moderately varnished surface.

Long

An allostratigraphic, piedmont-terrace unit above **Qay** and inset below **Qao**. The tread is typically ≤ 2 m above the **Qay** tread. A coarse and fine lithofacies are recognized. Both lithofacies are less consolidated

than the underlying Palomas Formation and lack buried soils (paleosols) with Bw or Bt horizons or Stage II+ to III carbonate horizons. The coarse lithofacies consists of sandy gravel and gravelly sand in tabular to lenticular beds. The gravel consists of pebbles, subordinate cobbles (up to 40%), and boulders (<10%). Gravel is typically clast-supported, subangular to subrounded, and composed of felsic-dominated volcanic rocks (mainly Vicks Peak Tuff). The sand is brown to light-brown, mostly coarse- to very coarse-grained (<20% fine to medium sand), subrounded (minor subangular), poorly sorted, and composed mainly of volcanic lithic grains. The fine lithofacies consists of massive, brown (7.5YR 5/4), very fine- to fine-grained sand with minor (up to 20%) clay-silt. This fine-grained sediment is overprinted by weak soil development (moderately developed, coarse, subangular blocky peds with few, faint clay films on ped faces and calcic horizon(s) with a Stage I to I+ carbonate development). Locally, the fine-grained lithofacies is a younger allostratigraphic subunit, derived largely from sheetflood reworking of windblown fines that backfill paleotopography after erosion of the coarse lithofacies. Together, the two lithofacies make up a 1- to 4-m-thick unit. The collective unit has a smooth geomorphic surface (lacking bar-and-swale topography) with a topsoil featuring an illuviated-clay (Bt) horizon underlying 1–20 cm of pale-brown sand. The desert pavement is weakly developed (weak clast varnish and low surface clast density).

Qao Older alluvium (middle Pleistocene)—

Poorly exposed sandy gravel and gravelly sand underlying terraces inset below the Cuchillo (**Qcsr** and **Qcslg**) and Aragon (**Qars**) geomorphic surfaces, and whose treads are above adjoining **Qai** and **Qay** surfaces. The tread of **Qao** is reddish-brown in aerial photography due clast varnishing, overturned clasts with orange varnish on their undersides, and/or Bt or Bw soil horizons in the topsoil. The deposit is 1–3 m thick.

Composite Units of Piedmont-terrace Deposits and Alluvium

Qaiyr Intermediate, younger, and recent alluvium (0 years old to late Pleistocene)—

Intermediate alluvium (**Qai**) and subordinate to subequal younger and recent alluvium (**Qay** and **Qar**, respectively); see detailed unit descriptions above. The deposit is generally several meters thick.

Qaiy Intermediate and younger alluvium (late Holocene to late Pleistocene)—

Intermediate alluvium (**Qai**) and subordinate to subequal younger alluvium (**Qay**); see detailed unit descriptions above. The deposit is generally several meters thick.

Qaoy Older and younger alluvium (late Holocene to middle Pleistocene)—

Older alluvium (**Qao**) and subordinate to subequal younger alluvium (**Qay**); see detailed unit descriptions above. The deposit is 1–4 m thick.

Qsa Sandy sheetflood and alluvial deposits filling swales on Cuchillo surface (Holocene to late Pleistocene)—

Short

Reddish-brown to brown, massive, clayey to silty, very fine- to fine-grained sand filling topographic swales on the Cuchillo geomorphic surface (**Qcsr** and **Qcslg**). The deposit is interbedded with coarser alluvium (sand and gravel) and overprinted by a cumulic soil lacking strong calcic horizons. This fine sediment gradationally overlies sandy gravel and gravelly sand. The deposit is moderately consolidated and 1–4 m thick.

Long

Reddish-brown to brown, massive, clayey to silty, very fine- to fine-grained sand filling topographic swales on the Cuchillo geomorphic surface (**Qcsr** and **Qcslg**). The deposit is interbedded with coarser

alluvium (sand and gravel) and typically overprinted by a cumulic soil. This soil exhibits pedogenic development (commonly moderate and subangular blocky) and typically lacks calcic horizons with greater than Stage I morphology. The sediment contains minor (<20%), scattered coarser sand and very fine to fine pebbles. The base of this fine sediment gradationally overlies sandy gravel and gravelly sand, which in turn overlies the Palomas Formation. The associated surface is smooth and lacks bar-and-swale topography. The deposit is moderately consolidated and 1–4 m thick.

Qsay Younger, sandy sheetflood and alluvial deposits (Holocene to late Pleistocene)—

Similar to unit **Qsa** but also mapped underlying smooth drainage floors inset below the Aragon geomorphic surface (**Qars**) in the southwestern part of the map area. The browner and darker, lower fine-grained sediment is capped by 10–40 cm of lighter-colored sand (grayish-brown to light-brownish-gray to pale-brown) typical of that seen in unit **Qay**. The deposit is moderately consolidated and 1–4 m thick.

Alluvial Fan Deposits

Qfy Younger alluvial fan deposits (late to middle Holocene) –

Gravel and sand, correlative to younger alluvium (unit **Qay**), underlying subtle, fan-shaped lobes on the low-sloping piedmont in the southwestern part of the map area. The surface is smooth but weakly varnished. The deposit is 1–5 m thick.

Qfiy Intermediate and younger alluvial fan deposits (late Holocene to late Pleistocene)—

Gravel and sand, correlative to intermediate and younger alluvium (**Qai** and **Qay**, respectively), underlying alluvial fans. There is weak to moderate varnish on the gravels. The surface is smooth and moderately vegetated. Its tread is a few meters lower than adjoining surfaces on **Qfo** or **QNpf**. The deposit is 1–5 m thick.

Qfi Intermediate alluvial fan deposits (middle Holocene to late Pleistocene)—

Gravel and sand, correlative to intermediate alluvium (unit **Qai**), underlying alluvial fans at the foot of steep slopes and fan-shaped lobes on relatively low-sloping piedmonts. The surface is weakly to moderately varnished. The deposit is 1–5 m thick.

Qfoi Older and intermediate alluvial fan deposits (middle Holocene to middle Pleistocene)—

Gravel and sand, correlative to older and intermediate alluvium (units **Qao** and **Qai**, respectively), underlying alluvial fans at the mouths of low-order drainages that drain steep terrain. The surface is weakly to well varnished and 4–11 m above adjoining **Qay** surfaces. The estimated thickness is 1–12 m.

Qfo Older alluvial fan deposits (late to middle Pleistocene)—

Short

Gravel and sand, correlative to the older alluvial unit (**Qao**), underlying alluvial fans at the foot of steep slopes. It also forms fan-shaped lobes on low-sloping piedmonts. The surface is moderately to strongly varnished and has a reddish-brown color. Its tread height relative to nearby **Qay** is 4–11 m. The deposit is locally inset below **QNpf** or onlaps proximal **QNpf**. Its thickness is about 2–12 m.

Long

Gravel and sand, correlative to the older alluvial unit (**Qao**), underlying alluvial fans at the foot of steep slopes. It also forms fan-shaped lobes on relatively low-sloping piedmonts. Its surface is moderately to strongly varnished and has a reddish-brown color due to varnishing, overturning of clasts with orange varnish on their undersides, and/or the presence of Bw or Bt horizons in the topsoil. The surface tends to be sparsely vegetated. The tread height of **Qfo** relative to adjoining **Qay** is 4–11 m. The deposit is locally inset below the **QNpf** surface or is a bouldery deposit that appears to onlap an eroding **QNpf** surface near the fan apex. The estimated thickness is 2–12 m.

Geomorphic Surfaces on Pleistocene Deposits

Qcsr Cuchillo geomorphic surface, reddish unit (late? to middle Pleistocene)

Short

Areas of the Cuchillo geomorphic surface that appear reddish-brown in aerial photography, likely due to surface clast varnishing or overturning of rubified undersides of these clasts, Bt or Bw soil horizon development, and (or) slopewash/sheetfloods reworking these soils. The Cuchillo surface (usage per McCraw and Williams [2012]) is developed on **Qnp** and **Qao** and lies ≈5–6 m below the Aragon geomorphic surface.

Long

Areas of the Cuchillo geomorphic surface that appear reddish-brown in aerial photography and are generally present in low-sloping, relatively stable geomorphic areas. The unit lies 1–5 m below the gray unit of the Cuchillo geomorphic surface (**Qcslg**). We interpret that the reddish-brown color is due to one or more of these factors: (1) surface clasts are moderately to strongly varnished; (2) Bt or Bw soil horizons immediately underlie the surface; (3) slopewash or sheetflood sediment is present, which has locally reworked the reddish brown Bt or Bw soil horizons into topographic lows; or (4) surface clasts with orangish, varnished undersides are overturned. The larger Cuchillo geomorphic surface is an extensive, slightly dissected surface developed on the Palomas Formation (**Qnp**) that extends across most of the southern half of the quadrangle. The Cuchillo geomorphic surface (usage per McCraw and Williams [2012]) postdates the Aragon geomorphic surface and is interpreted to reflect pediment-style erosion and then relative stability in the proximal piedmont region.

Qcslg Cuchillo geomorphic surface, grayish unit (late? to middle Pleistocene)

Short

Areas of the Cuchillo geomorphic surface that appear light gray in aerial photography and lie 1–5 m above **Qcsr**. Based on limited observations, the soils of this unit lack Bt and Bw horizons, clast varnishing is minimal, and it has calcic horizons that are less developed than Stage IV. The Cuchillo geomorphic surface (usage per McCraw and Williams [2012]) is developed on **QNp** and **Qao** and lies ≈5–6 m below the Aragon geomorphic surface.

Long

Areas of the Cuchillo geomorphic surface that appear light gray in aerial photography and lie 1–5 m above the reddish unit of the Cuchillo geomorphic surface. Based on limited observations, the soils of this unit lack Bt and Bw horizons, clast varnishing is minimal, and it has calcic horizons less developed than Stage IV. The larger Cuchillo geomorphic surface is an extensive, slightly dissected surface developed on the Palomas Formation (**QNp**) and older alluvium (**Qao**) that extends across most of the southern half of the quadrangle. The Cuchillo geomorphic surface (usage per McCraw and Williams [2012]) postdates the Aragon geomorphic surface and is interpreted to reflect pediment-style erosion and then relative stability in the proximal piedmont region.

Qars Aragon geomorphic surface (early Pleistocene)

Short

Surface mapped over moderately dissected terrain on the west-central section of the map, west of Aragon Wash. It projects eastward about 5–6 m over the adjoining Cuchillo geomorphic surface to the east. The surface is also present on the northeastern portion of the map. The surface consists of relatively broad (50–200 m wide), concordant ridges and exhibits a local relief of 5–10 m.

Long

Geomorphic surface mapped over moderately dissected terrain on the west-central section of the map, west of Aragon Wash. It projects eastward about 5–6 m over the adjoining Cuchillo geomorphic surface to the east. The surface is also present on the northeastern portion of the map. The surface consists of relatively broad (50–200 m wide), concordant ridges and exhibits a local relief of 5–10 m. The Aragon geomorphic surface is thus considered older than the Cuchillo geomorphic surface and is interpreted to represent the culmination of the Santa Fe Group in the proximal part of the piedmont in this part of the basin.

Santa Fe Group

The Santa Fe Group is a name applied to synextension, clastic basin fill of the Rio Grande rift and includes interbedded or intercalated volcanic flows (Baldwin, 1956; Spiegel and Baldwin, 1963). Only the uppermost strata of the Santa Fe Group crop out in the map area.

Qb Basanite (early Pleistocene)—

Massive, black to very dark-gray, aphanitic basanite containing plagioclase laths ≤ 0.2 mm long. The basanite is locally a scoria. There are also 0.5% olivine phenocrysts ≈ 2 mm across. A ≈ 1 -m-wide, north-trending dike is present. The unit is poorly exposed. Groundmass $^{40}\text{Ar}/^{39}\text{Ar}$ age is 2.51 ± 0.03 (this report: 290000m E, 3701800m N).

QNpf Palomas Formation under alluvial fan landforms (early Pleistocene to middle Pliocene)—

Gravelly Palomas Formation strata underlying distinctive alluvial fan landforms adjacent to steep-sloped bedrock. Strata are commonly light-gray in aerial imagery due to inferred erosion. See description of unit **QNp** below.

QNp Palomas Formation (early Pleistocene to middle Pliocene)—

Short

Sandy gravel and minor pebbly sand in thin to thick, tabular to lenticular beds. Gravel consists of pebbles with ≈20–30% cobbles and 1–10% boulders. Gravel matrix mostly consists of medium- to very coarse-grained sand that has 1–15% clay in the matrix, imparting a reddish color. Local paleosols with orangish Bt or Bw horizons overlie calcic horizons. The thickness likely ranges from 10 to 200 m.

Long

Sandy gravel and minor pebbly sand in thin to thick, tabular to lenticular beds. Gravel consists of pebbles with lesser cobbles (≈20–30%) and boulders (<10%). Gravel clasts are subangular to subrounded, poorly sorted, and composed of felsic-dominated volcanic rock (with abundant Vicks Peak Tuff, **P_vvpt**); clast imbrication is common. Gravel matrix consists of sand that is medium- to very coarse-grained (minor very fine to fine sand), subangular to subrounded, poorly sorted, and composed primarily of volcanic-lithic grains (very minor feldspar and quartz). Variable clay (commonly 1–15% of volume) occurs in the matrix (as coats on grains and filling interstitial voids) and imparts a reddish to light-reddish-brown color. Calcium carbonate precipitation is absent or very minor (no to very weak HCl effervescence). The deposit is well consolidated and weakly cemented by clay. There are local paleosols with orangish to reddish Bt or Bw horizons overlying calcic horizons (up to Stage III carbonate morphology). The surface of the Palomas Formation is relatively gravelly, with abundant pebbles and cobbles. This surface commonly corresponds to the Aragon or Cuchillo geomorphic surfaces. Undersides of clasts are commonly rubified. Thickness is unknown but is probably at least tens of meters and up to 200 m in the southeastern part of the map area (per cross section of Cikoski and Koning, 2013).

PALEOGENE

Intrusive Igneous Units

P_{ir} Rhyolitic intrusions (late Oligocene)—

Short

Rhyolite domes containing 20–35% quartz (1–4 mm) and sanidine (1–3 mm) and trace biotite (≤ 1 mm) in a fine-grained white matrix. The unit displays large-scale flow banding, possibly from extrusive dome building. The margin of the intrusion is commonly xenolith-rich and is commonly associated with brecciated host rock, typically Vicks Peak Tuff (**Fvpt**). Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 28.36 ± 0.02 to 28.46 ± 0.04 Ma (this report).

Long

Rhyolite domes containing 20–35% quartz (1–4 mm) and sanidine (1–3 mm). Also has trace biotite (≤ 1 mm) in a fine-grained white matrix. Some sanidine is chatoyant. The unit displays large-scale flow banding, possibly from extrusive dome building. The expression of rhyolite at the margin of the intrusion is variable but is commonly xenolith-rich. The intrusion can appear quenched and glassy at the margin and commonly contains large, rounded xenoliths of various igneous compositions. Where the intrusion has assimilated foreign rocks, it often appears reddish in color. Where small-scale “dikelets” have broken off from the main body of the intrusion, their margins are typically characterized by quenched rhyolite, a silicified angular xenolith-rich breccia, and brecciated host rock. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 28.36 ± 0.02 to 28.46 ± 0.04 Ma (this report).

Extrusive Volcanic and Volcaniclastic Units

F_r Rhyolite flow (late Oligocene)—

Short

Pink to gray, flow-banded rhyolite lava that is generally aphanitic. Unit contains sparse quartz and sanidine phenocrysts typically 0.5–1 mm (≤ 5 mm), which are aligned with flow banding. Flow brecciation and botryoidal hematite mineralization are present. Unit has a rheomorphic green-blue, glassy base. Unit has a minimum thickness of ≈ 12 –18 m, but top of unit may have been eroded in the map area.

Long

Pink to gray, flow-banded rhyolite lava flow that is generally aphanitic. The unit contains sparse quartz and sanidine phenocrysts ≤ 5 mm, typically 0.5–1 mm. Where present, phenocrysts are aligned with flow banding. Mild flow brecciation is common, as is botryoidal hematite mineralization. The unit displays a green-blue, glassy base with rheomorphic textures. The rhyolite overlies a fragmental hydromagmatic deposit, which is reworked into the glassy base of the flow. The unit has a minimum thickness of ≈ 12 –18 m, but the top of the unit may have been eroded in the map area. The unit may be related to the Springtime Canyon quartz latite flow of Fouria (1984).

F₂tl Local quartz-bearing tuff (late Oligocene)—

Light- to dark-brown, crystal-rich, lithic-rich, glassy tuff with 10–25% sanidine and quartz, <1% biotite, and trace hornblende. Unit contains 2–15% lithics (≤ 11 cm long) in an ashy matrix. Locally, the unit has a black, glassy basal vitrophyre and caps a white volcanoclastic sandstone. The unit has limited exposure in the map area and is likely a local unit. The maximum exposed thickness is ≈ 18 m.

F₂vpt Vicks Peak Tuff (early Oligocene)—

Short

Light-gray, crystal-poor tuff with 0.5% euhedral sanidine (0.5–2.0 mm). Spherulites 2–4 cm in diameter are common. Moderately to very strongly welded with 2–5% fiamme (≤ 1 mm thick and 1–10 cm long).

Commonly strongly foliated. Commonly has black, glassy basal vitrophyre. At least ≈180 m thick in the northern half of the map area. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ age is 28.80 ± 0.03 Ma (this report).

Long

Light-gray, crystal-poor tuff with 0.5% euhedral sanidine crystals (0.5–2.0 mm). Spherulites 2–4 cm in diameter are common. Moderately to very strongly welded with 2–5% fiamme up to 1 mm thick. Fiamme are typically 1–10 cm long. In the northern part of the map area, the unit is typically strongly foliated with a strong eutaxitic texture. The unit locally contains small (0.5–1.5 cm long) fractures inferred to be tension features related to the flow of the viscous tuff. The unit commonly displays a dark-gray to black, glassy basal vitrophyre. In some places, the basal vitrophyre has a marbled appearance with chaotic rheomorphic textures. The vitrophyre minimum thickness is ≈2 m. The unit often weathers to produce broad areas of talus and gravelly colluvium (**Qct** and **Qcd**, respectively), where the matrix between clasts is often reddish. The unit is at least ≈180 m thick in the northern half of the map area. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ age is 28.80 ± 0.03 Ma (this report).

Alteration Zones of F_{vpt} (Oligocene?)

F_{vpts} **Silicified Vicks Peak Tuff (Oligocene?)**—Brown **F_{vpt}** altered to silica. Commonly weathers to tall, rounded pillars.

F_{vptw} **White, kaolinized Vicks Peak Tuff (Oligocene?)**—White, punky **F_{vpt}** altered to kaolinite. The unit is rough and friable. Distinctive small-scale tension fractures observed in **F_{vpt}** are well preserved in this unit.

F_{vptb} **Brecciated Vicks Peak Tuff (Oligocene?)**— **F_{vpt}** brecciated to tight, angular, clast-sized chunks. Stilbite mineralization is common throughout the breccia. No visible matrix between angular Vicks Peak Tuff clasts. Commonly occurs adjacent to **F_{ir}** but can be found throughout the northern portion of the map area where there is no visible **F_{ir}** .

$\text{P}\ell\text{j}\text{p}$ La Jara Peak basaltic andesite (early Oligocene)—

Short

Aphanitic, reddish-brown to black basaltic andesite with variable vesicularity. Vesicles commonly coated in light-green mineralization or filled with light-tan clay alteration. Unit is commonly highly altered to a dull, light-tan to yellow color or a glassy, brecciated, orangish-brown color. Thickness variable over short distances, likely a result of paleotopography. Unit is 5–33 m thick.

Long

Aphanitic, reddish-brown to black basaltic andesite. The vesicularity of the unit is highly variable. Where present, vesicles are commonly coated in light-green mineralization or filled with light-tan clay alteration. The unit is typically highly altered, especially south of Ducknest Tank. Where altered, the unit is a dull, light-tan to yellow color or a glassy, brecciated, orangish-brown color. The thickness is variable even over short distances, likely a result of the unit filling paleotopography. The unit is 5–33 m thick.

$\text{P}\ell\text{j}\text{t}$ La Jencia Tuff (early Oligocene)—

Short

Orange to brown to gray, crystal-poor tuff with 5–10% fiamme and 3–10% phenocrysts of sanidine. Occasionally has a dark, glassy vitrophyre. More poorly welded and grayish, with 5–10% phenocrysts and \approx 3–8% lithics upsection. Sharply overlies $\text{P}\ell\text{dwt}$ or $\text{P}\ell\text{ipt}$ and is 10–25 m thick. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages are between 29.00 ± 0.03 and 29.02 ± 0.02 Ma (this report).

Long

Light-orange to reddish-brown to gray, crystal-poor tuff with 5–10% fiamme. The lower part of the unit is typically pinkish to orangish in color and has 3–10% phenocrysts of sanidine and 5–10% black,

flattened fiamme. The base of the unit commonly has a glassy, gray to black vitrophyre that is more lithic-rich (up to 15% lithics and fiamme) in the central part of the map area, but this vitrophyre is absent in the west-central part of the area. Upsection, the unit becomes more poorly welded and gray to pinkish-gray in color, with 5–10% phenocrysts and ≈3–8% lithics. Fiamme in this more poorly welded section are typically less flattened and often manifest as weathered, devitrified cavities. The unit lies sharply above the Datil Well Tuff (**P_{dwt}**) or the Luna Park Tuff (**P_{lpt}**) and is 10–25 m thick. Tentatively correlated with the La Jencia Tuff, which has a previously published age of 29.00 ± 0.01 Ma (Cather et al., 2024; sample from north of the map area). Sanidine ⁴⁰Ar/³⁹Ar ages are between 29.00 ± 0.03 and 29.02 ± 0.02 Ma (this report).

P_{hm} Hells Mesa Tuff (early Oligocene)—

White to pink to peach-colored, lithic-poor (<5%), moderately welded tuff with 5–7% phenocrysts of quartz, biotite, sanidine, titanite, and sparse hornblende. It has an ⁴⁰Ar/³⁹Ar age of 32.35 ± 0.01 Ma from a sample north of the quadrangle (Cather et al., 2024). The thickness is variable, ranging from 1 to 3 m.

P_{dwt} Datil Well Tuff (late Eocene)—

Short

Strongly welded, crystal-rich tuff with 3% lithics, 3–5% fiamme, and 25–30% phenocrysts of sanidine (≤4 mm) and lesser biotite (≤2 mm). Reddish-brown to maroon color. Upsection, the unit becomes gray and less welded, with 5–15% phenocrysts and 3–7% lithics. Thickness varies from ≈15 to ≈80 m but appears to pinch out to west. Sanidine ⁴⁰Ar/³⁹Ar age is 35.41 ± 0.02 Ma (this report).

Long

Strongly welded, crystal-rich tuff with 3–5% fiamme (1–10 mm thick and 3–8 cm long). Fresh color of pinkish to reddish-brown and weathered color of brownish-gray to light-maroon. The unit contains 25–

30% phenocrysts of sanidine (subhedral [minor euhedral] and 0.5–2.0 mm [minor up to 4.0 mm] long) and trace to 0.5% biotite (subhedral and 0.5–2.0 mm long). The tuff contains 3% lithic fragments, typically intermediate volcanic rocks 0.5–3.0 cm long. Upsection, the unit becomes gray, less crystalline (5–15% phenocrysts), more lithic-rich (3–7%), and more weakly welded. The tuff ranges in thickness from ≈15 to ≈80 m but appears to be absent in the western part of the quadrangle. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ age is 35.41 ± 0.02 Ma (this report).

Fe|pt Luna Park Tuff (late Eocene)—

Short

Light-brown to pink, crystal-rich tuff with 15–30% sanidine, 2–3% pyroxene, <3% biotite, 10% fiamme (≤ 4 cm), and 5–30% lithics (≤ 30 cm). Upsection, the unit is lighter in color and less welded and contains up to 5% biotite up-section. Up to ≈150 m thick in the eastern part of the map area. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages are between 35.76 ± 0.03 and 35.72 ± 0.02 Ma (this report).

Long

Light-brown to pink, crystal-rich tuff with 15–30% sanidine, 2–3% pyroxene, <3% biotite, ≈10% fiamme (up to 4 cm long), and 5–30% lithics (up to ≈30 cm). The unit fluctuates between moderate and strong welding. Where there are abundant lithics, the tuff is usually less welded and is white to gray.

Upsection, the tuff becomes lighter in color and less welded and contains more copper-colored biotite (up to ≈5%). In some areas, such as Rimrock Ridge, **Fe|pt** is pink and fine-grained at the base, with rare lithics. A black, glassy vitrophyre is occasionally present at the base. The unit's thickness varies from ≈40 m in the west to ≈150 m in the eastern part of the map area. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages are between 35.76 ± 0.03 and 35.72 ± 0.02 Ma (this report).

Fe|td Tuff of Aragon Draw (late Eocene)—

Short

Light-red to purple to brown, crystal-poor tuff with 1–15% sanidine phenocrysts (≤ 6 mm). Strongly welded. Highly rheomorphic. Brown variety has 10–15% chalky sanidine, trace biotite, and $\leq 35\%$ lithics (commonly white and dacitic). Red to purple variety contains $< 10\%$ sanidine, trace biotite, 20–25% fiamme, and $\leq 25\%$ lithics. Unit is 6–46 m thick. Previously published age of 36.11 ± 0.03 Ma (Koning et al., 2014).

Long

Light-red to purple to brown, crystal-poor tuff with 1–15% sanidine phenocrysts (1–2 mm, up to 6 mm). The unit is strongly welded and highly rheomorphic, with fiamme often appearing swirly. Two varieties of the unit are observed in the map area: a reddish, crystal-poor tuff and a brown tuff. The brown tuff is observed in both the east and west sides of the map area and typically has 10–15% chalky sanidine, trace biotite, and up to 35% lithics. The lithics in the brown tuff are commonly white and dacitic in composition. The reddish to purplish tuff is abundant in the west side of the map area, where it typically has 1–10% sanidine crystals, trace biotite, and up to 25% lithics. The fiamme in the red tuff are commonly 5–6 cm long and very swirly. The reddish tuff becomes crystal-poor and lithic-poor in the eastern part of the map area. The unit locally displays a black, glassy vitrophyre. **P₁tad** interfingers with **P₁sl**, particularly on the west side of the map area. The unit commonly fills in paleovalleys, resulting in variable thickness, but is generally thicker on the west side of the map area, with a maximum observed thickness of 46 m, and a minimum thickness of ≈ 6 m on the east side of the map area. Previously published age of 36.11 ± 0.03 Ma (Koning et al., 2014).

Spears Group

NP₁sc Seferino Hill conglomerate (early Miocene? to late Oligocene)—

Matrix-supported, massive, very poorly sorted conglomerate. Clasts are angular to subangular and composed of **F_{evpt}**. The unit consists of 50% pebbles, 30% cobbles, and 20–25% boulders in a red matrix of fine-grained sand, clay, and lesser coarser sand composed of angular to subangular **F_{evpt}** and trace andesite. The unit is 5–8 m thick.

F_{esu} Upper Spears Group sediments (late to early Oligocene)—

Weakly to moderately cemented volcanoclastic sandstones and conglomerates. The unit is coarser-grained at the base, with subangular, cobble-sized clasts typically of **F_{evpt}** composition. Unit fines upsection, with alternating beds of poorly sorted fine- to coarse-grained sandstone and moderately sorted fine- to medium-grained sandstone. The top of the unit is not exposed and minimum thickness is ≈18 m.

F_{esm} Middle Spears Group sediments (late Eocene)—

Short

Poorly to moderately sorted, medium- to coarse-grained sandstone and minor conglomerate. Color is light-brown to white. Commonly contains subhedral feldspar and hornblende grains in an ashy, sandy matrix. Beds are typically 0.5–1.0 m thick. Locally contains intervals of homogeneous white ash. The unit is discontinuous and 25–45 m thick where present.

Long

Weakly to moderately cemented, poorly to moderately sorted, medium- to coarse-grained sandstone with minor conglomeratic interbeds. Fresh color is light-brown to white. The unit commonly contains subhedral feldspar and hornblende grains in an ashy, sandy matrix. Beds are typically 0.5–1.0 m thick. Poorly sorted sandstone intervals often contain accumulations of pebble-sized pumice clasts at the top of the interval. Infrequent conglomeratic intervals contain intermediate-composition lithic clasts up to

≈35 cm. The unit contains occasional intervals of homogeneous white ash that are ≈10–20 cm thick. The unit is 25–45 m thick and is absent in some sections of the map area.

P_{esl} Lower Spears Group sediments (late to middle Eocene)—

Short

Volcaniclastic sandstones and debris flows. Debris flow intervals are massive and very poorly sorted and contain pebble- to boulder-sized volcanic clasts in a well-cemented, ashy matrix. Sandstone intervals are fine- to coarse-grained and vary from ashy-white to green to light-brown. Unit interfingers with unit **P_{ert}** and fills paleotopography within **P_{erd}**. Unit has a minimum thickness of ≈45 m.

Long

Weakly to well-cemented volcaniclastic sandstones and debris flows. Debris flow intervals are massive and very poorly sorted and contain pebble- to boulder-sized andesite and tuff clasts in a well-cemented, fine-grained, ashy matrix. Sandstone intervals are fine- to coarse-grained. Color varies from ashy-white to green to light-brown. Sandstone locally has 15- to 30-cm-thick beds. Unit **P_{esl}** interfingers with unit **P_{ert}** north of Peñasco Spring and fills paleotopography within **P_{erd}**. The unit has a minimum thickness of ≈45 m.

P_{eslr} Lower Spears Group sediments, red (middle Eocene)—

Short

Fine- to coarse-grained sandstone, locally pebbly. Unit is poorly to moderately sorted and moderately to strongly cemented. Color is typically light-brown but locally has a reddish hue. In coarse-grained layers, there are ≈2 mm subhedral crystals of hornblende, biotite, and feldspar. Strata are thin- to medium-bedded. Unit is thinner to the south (≈2 m) and becomes thicker to the north (≈75 m).

Long

Moderately to strongly cemented, fine- to coarse-grained sandstone with local pebble-bearing intervals. The unit is poorly to moderately sorted. Color is typically light-brown but locally takes on a reddish hue with stringers of very fine-grained, red veins that crosscut stratigraphy. In coarse-grained layers, ≈2 mm subhedral crystals of hornblende, biotite, and feldspar are present. Where described, strata are in 5- to 15-cm-thick beds that are commonly laminated.

The unit is thinner to the south (≈2 m) and becomes thicker to the north (≈75 m).

Red Rock Ranch Formation

PERU Red Rock Ranch Formation, undivided (late to middle Eocene)—

Short

Gray, intermediate lavas and volcanoclastic sediments. Lavas contain up to 20% phenocrysts of hornblende, feldspar, and pyroxene and are commonly flow-brecciated. Also contains coarse-grained debris flow deposits of **PERsl**. Forms a lag deposit north of Peñasco Spring. Includes smaller outcrops of unit **PERt** where it was too small to map separately. Maximum observed thickness of ≈145 m.

Long

Dark- to light-gray, intermediate lavas containing up to 20% phenocrysts of hornblende, feldspar, and pyroxene. Lavas commonly display flow brecciation. The unit also locally contains coarse-grained debris flow deposits of the lower Spears Group (**PERsl**) where the units are difficult to distinguish from one another. The unit forms a broad lag deposit north of Peñasco Spring, leaving behind abundant subrounded andesite float (pebbles to boulders) without any apparent outcrop. The unit includes some smaller outcrops of unit **PERt** where it was too small to map separately. The unit has a maximum observed thickness of ≈145 m.

Peraw Plagioclase-pyroxene andesite flow, west (middle Eocene)—

Reddish- to purplish-brown, aphanitic to equigranular andesite. Phenocrysts are 65–70% anhedral to subhedral plagioclase (0.1–1.0 mm), with 1–3% green pyroxene (0.1–1.5 mm) and 1–3% hornblende up to 8 mm long. Minimum thickness of 35 m.

Perf Pyroxene-plagioclase trachyandesite flow (middle Eocene)—

Short

Reddish-brown to gray, variably vesicular trachyandesite with 10–15% phenocrysts of pyroxene, plagioclase, and hornblende (typically <2 mm). The vesicular variety typically has green mineralization coating the vesicles. The unit's thickness varies over short distances north of Peñasco Spring; it is 8–20 m thick where interbedded with unit **Perl** and at least 65 m thick northwest of Peñasco Spring.

Long

Reddish-brown to gray trachyandesite. Lava contains 10–15% phenocrysts of pyroxene, plagioclase, and hornblende (typically <2 mm). This unit includes both vesicular and nonvesicular trachyandesites. Vesicular trachyandesite typically has abundant green mineralization coating the vesicles and appears to host chalcedony (seen in float). The unit's thickness varies over short distances north of Peñasco Spring; it is 8–20 m thick where interbedded with unit **Perl** and at least 65 m thick northwest of Peñasco Spring. The unit is correlative to the Red Rock Arroyo andesite unit of Koning et al. (2014).

Perb Basaltic trachyandesite flow (middle Eocene)—

Light-gray, aphanitic, basaltic trachyandesite with 3% pyroxene and possible amphibole (1–2 mm). The unit is primarily observed as clasts, which exhibit strong varnish.

Perd Hornblende-plagioclase dacite flow (middle Eocene)—

Short

Dacite, trachydacite, and trachyandesite with 5–15% phenocrysts of subhedral hornblende (≤ 3 mm), subhedral to anhedral plagioclase (0.1–1.0 mm), trace biotite and pyroxene (≤ 1 mm). Porphyritic to equigranular, typically massive, locally brecciated and flow banded. Unit has a maximum thickness of 173 m. Plagioclase and hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 39.12 ± 0.16 to 40.99 ± 0.12 Ma (this report).

Long

Light-gray weathering to reddish-brown, intermediate lava flows spanning the compositional range of dacite to trachydacite to trachyandesite. The unit has 5–15% phenocrysts of subhedral to euhedral hornblende (≤ 3 mm, mostly 0.5–1.0 mm) and trace to 1% biotite and pyroxene (≤ 1 mm, subhedral to euhedral). The remainder of the rock consists of subhedral to anhedral plagioclase whose crystals are well-graded, ranging from 0.1–1.0 mm, locally with a small proportion up to 2 mm. Texture varies from porphyritic to equigranular. The lavas locally exhibit auto-brecciation. Flow banding is common on the ridge east of Flying X Ranch, but elsewhere the lavas are typically massive. The unit is typically tens of meters thick, with the maximum observed thickness being 173 m at 2.5 km northeast of Flying X Ranch. Plagioclase and hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 39.12 ± 0.16 to 40.99 ± 0.12 Ma (this report).

F₁rta Trachyandesite flow, aphyric (middle Eocene)—

Aphyric, medium-gray trachyandesite. The unit contains 2% typically chalky plagioclase (2–3 mm, anhedral to subhedral), $\approx 2\%$ hornblende, and 1% biotite. Mafic crystals are typically 0.5–1.0 mm. The unit forms relatively small, “nubby” exposures with hackly fracturing.

F₁rdp Plagioclase-phyric dacite flow (middle Eocene)—

Short

Dacite to trachydacite to andesite with 10–15% anhedral to subhedral plagioclase phenocrysts (≤ 7 mm long), commonly altered; 5–13% mafics (≤ 3 mm); trace to 1% quartz. Lavas commonly have a lower flow-breccia unit, locally are flow banded (e.g., 4 km southwest of Peñasco Spring), and have a maximum thickness of ≈ 160 m. Plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 39.98 ± 0.14 to 40.1 ± 0.15 Ma (this report).

Long

Medium-gray weathering to light-orangish-brown, intermediate lavas spanning the compositional range of dacite to trachydacite to andesite. The lava has 10–15% anhedral to subhedral, conspicuous plagioclase phenocrysts ≤ 7 mm long (mostly 2–5 mm). Where the unit has been altered, plagioclase is often chalky white. Other phenocrysts are 5–13% mafics, including hornblende (≤ 3 mm) and biotite (≤ 2 mm), and trace to 1% quartz. The lavas commonly have a lower, red-tinged flow-breccia unit. Lavas are flow banded in low hills 4 km southwest of Peñasco Spring and have hackly/vertical fracturing in the twin hills south of Rimrock Ridge. The unit has a maximum observed thickness of ≈ 160 m. Plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ ages range from 39.98 ± 0.14 to 40.1 ± 0.15 Ma (this report).

PALEOZOIC ROCKS

Permian

Pa Abo Formation (late to middle Wolfcampian)—

Brick-red to reddish-brown mudstone with 25–30% ledge-forming, strongly cemented siltstone and very fine-grained sandstone (minor fine-grained sand). The unit is in thin to medium, tabular beds that are distinctly horizontally or ripple mark-laminated. Mudstone is poorly exposed and inferred from descriptions of nearby outcrops (e.g., Seager and Mack, 2003; Lucas et al., 2012c).

Pennsylvanian

IPgm Gray Mesa Formation (Desmoinesian)—

Short

Micritic and massive limestone interbedded with laminated sandy limestone and brick-red, fine-grained sandstone. Both the micritic and sandy limestones contain fossils that include bivalves, brachiopods, and gastropods. Within the micritic limestone, there are local boulder-sized, yellow chert nodules, which often appear brecciated with the limestone. Strata have a minimum thickness of ≈92 m.

Long

Micritic and massive limestone interbedded with laminated sandy limestone and brick-red, fine-grained sandstone. Both the micritic and sandy limestones contain fossils that include bivalves, brachiopods, and gastropods. Interbedded red sandstones are often chaotic, displaying what appears to be soft sediment deformation. Within the micritic limestone, there are occasionally boulder-sized, yellow chert nodules, which often appear brecciated with the limestone. The unit also occasionally contains large crystalline veins of calcite within the limestone intervals. Strata have a maximum observed thickness of ≈92 m but the base of the unit is not exposed, so this is a minimum estimate.

SUBSURFACE UNITS

IPbb Bar-B Formation (upper Desmoinesian to Missourian)—

Dark-gray to dark-brownish-gray, thin- to medium-bedded limestone overlain by shale and conglomerate (containing pebbles and granules of limestone, dolostone, and chert). The unit is approximately 75 m thick. From Koning et al. (2012).

IPrh Red House Formation (upper Morrowan to Atokan)—

Interbedded, maroon to pinkish-white, quartzose sandstone and conglomerate, dark-gray shale, and light-gray- to yellowish-tan-weathering limestone. The unit is approximately 555 m thick. From Koning et al. (2012).

Pzu Lower Paleozoic strata, undivided (Ordovician to Cambrian) –

Includes the Bliss Sandstone, El Paso Group, and Montoya Formation. Cikoski and Koning (2013) inferred a thickness of ≈ 230 m from the West Elephant Butte Federal No. 1 well, but we use a thickness of ≈ 150 m given that these units pinch out to the north.

ZYu Proterozoic strata, undivided (Neoproterozoic to Mesoproterozoic) –

Meta-sandstone, quartzite, quartz or quartz-biotite schist, amphibolite schist and gneiss, and intercalated granite and granite-gneiss (Koning et al., 2018).