Geologic Map of the Hillsboro 7.5-Minute Quadrangle, Sierra County, New Mexico

Report

by

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Open-file Digital Geologic Map OF-GM 242

Scale 1:24,000

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GEOLOGY OF THE HILLSBORO QUADRANGLE, SIERRA COUNTY, NEW MEXICO

Cover photo: View looking west from Empire Peak area. Foreground rocks include andesite and breccia of Copper Flat. Pliocene basalts and Paleogene volcanic strata make up the middleground, and the Black Range forms the skyline.

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INTRODUCTION

This report accompanies the *Preliminary Geologic Map of the Hillsboro 7.5-Minute Quadrangle, Sierra County, New Mexico* (NMBGMR OF-GM 242). Its purpose is to discuss the geologic history of the Hillsboro area, and to identify and explain significant relationships uncovered during the course of mapping. Included is a summary of the geothermal potential of this area.

The Hillsboro quadrangle is bound by the eastern Black Range in western Sierra County, New Mexico, with its eastern edge extending into the Palomas Basin. The Animas Hills (Animas horst) bisect the quadrangle and include the Copper Flat mine, surrounded by peaks and high ridges reaching over 6000‘ above sea level. Among these are Animas Peak (6170‘), Black Peak (6251‘), and the highest point in the quadrangle, Empire Peak (6454‘). The lowest point in the quadrangle is where Percha Creek exits the map‘s eastern boundary at approximately 4840‘. Percha Creek is the main drainage in the quadrangle; other significant drainages include Tank Canyon in the north and Trujillo Creek in the south. Most land in the quadrangle is privately owned, although Bureau of Land Management (BLM) sections may be found in the east and southwest. Access is provided by NM-152, NM-27, and dirt roads traversing ranches throughout the area.

Hedlund (1977) and Seager (1986) previously mapped the area at 1:48,000 scale. An early geochemical exploration of the eastern Black Range and Copper Flat is provided by Alminas and Watts (1978). More recent accounts of the mineralogic evolution of Copper Flat are given by McLemore et al. (1999) and McLemore et al. (2000).

The four primary geologic components mapped in the quadrangle are: (1) Cretaceous andesite flows, laharic breccias, and intrusive bodies of Copper Flat; (2) pervasively faulted and/or altered Paleozoic strata north and south of Copper Flat; (3) well-preserved Tertiary (upper Eocene-Oligocene) volcanic stratigraphy in the western part of the quadrangle; and (4) Miocene basin-fill in the east-tilted Animas graben running down the center of the quadrangle and including the town of Hillsboro. Each of these components are discussed individually in the report, which includes a geologic setting and summary of local geochronology data before describing mapped units and their depositional settings by age, oldest to youngest. The structural geology and geothermal potential of the area are then described, and detailed unit descriptions are provided as an appendix.

ACKNOWLEDGEMENTS

Mapping of the Hillsboro quadrangle was funded by the STATEMAP program, which is jointly supported by the U.S. Geological Survey and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR). We thank J. Michael Timmons of NMBGMR for logistical support. We kindly thank the Bason, Roberts, and Thornton families for permission to work on their ranch properties. We appreciate the aid of Dr. Barry Kues (University of New Mexico) in identifying Devonian and Pennsylvanian fossil specimens. Dr. Virgil Lueth (NMBGMR) provided important insights into the possible origin of the paleokarst features in the vicinity of Copper Flat.

GEOLOGIC SETTING

Hillsboro is situated in the southern part of the Rio Grande rift, a series of *en echelon* basins stretching from northern Colorado to Chihuahua, Mexico. The quadrangle includes the Animas horst and east-dipping half-graben, which separates the Palomas Basin to the east from the Black Range to the west (Figure 1). The Palomas Basin is a ~25 km wide half-graben tilted eastward toward west-down, mountain-bounding faults of the Caballo Mountains. Structures created during three major tectonic episodes intersect in the Hillsboro area: (A) the NW-striking Rio Grande reverse fault that formed during Laramide deformation; (B) the Emory caldera that collapsed during Mogollon-Datil volcanic field development; and (C) north-striking, west-dipping normal faults that developed during rift extension (Figure 2). The latter faults include the Lake Valley fault in the west and the Berrenda fault bounding the west side of Copper Flat and extending beyond the southern end of the quadrangle. Hedlund (1977) mapped the Berrenda fault as the ―Snake” fault in the lower part of Warm Springs Canyon. Relationships between these features in the northern part of the quadrangle are illustrated in Figure 3. Additionally, the Animas fault is found on the east side of Copper Flat.

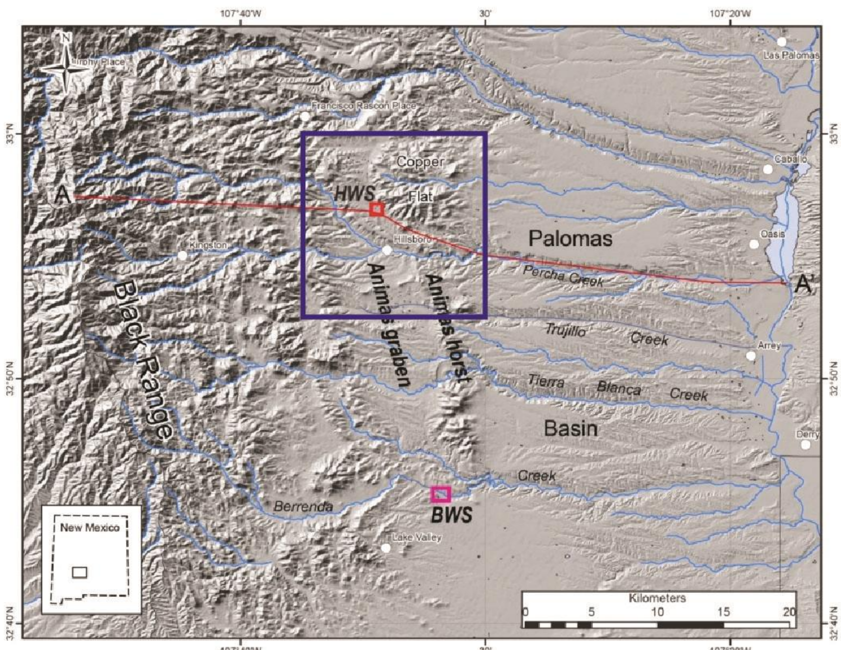

Figure 1. Location map of the Hillsboro quadrangle (dark blue box). The quadrangle includes both the Animas horst and Animas graben. HWS = Hillsboro warm springs, BWS = Berrenda warm springs. Modified from Kelley et al. (2014).

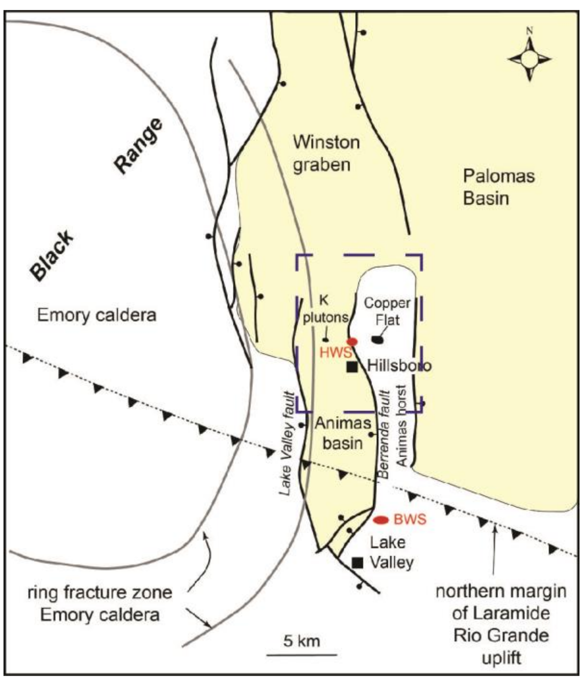

Figure 2. Generalized structure map of the Hillsboro area. Approximate outline of quadrangle in dark blue. Modified from Kelley et al. (2014).

Late Cretaceous to Paleogene Laramide transpressive deformation formed prominent NW- and W-striking structural fabrics controlling permeability and fluid flow in this region (Seager et al., 1986). The northeastern edge of the Laramide Rio Grande uplift lies between Silurian carbonate exposures on the hanging wall just north of Berrenda Creek and Pennsylvanian exposures on the footwall within the east-dipping Animas horst between Lake Valley and Hillsboro (O'Neill et al., 2002). The Rio Grande uplift and its contemporary, the Love Ranch basin to the north, are now primarily buried by younger rift-fill sedimentary deposits in the Palomas and Animas basins (Seager and Mayer, 1988). Plutons of Cretaceous age were emplaced at Copper Flat northeast of Hillsboro and in an area 8 km northwest of Hillsboro (Figure 2; Seager et al., 1982). The Cretaceous andesitic stratovolcano at Copper Flat is composed primarily of well-indurated volcaniclastic debris flows intercalated with a few andesitic lava flows.

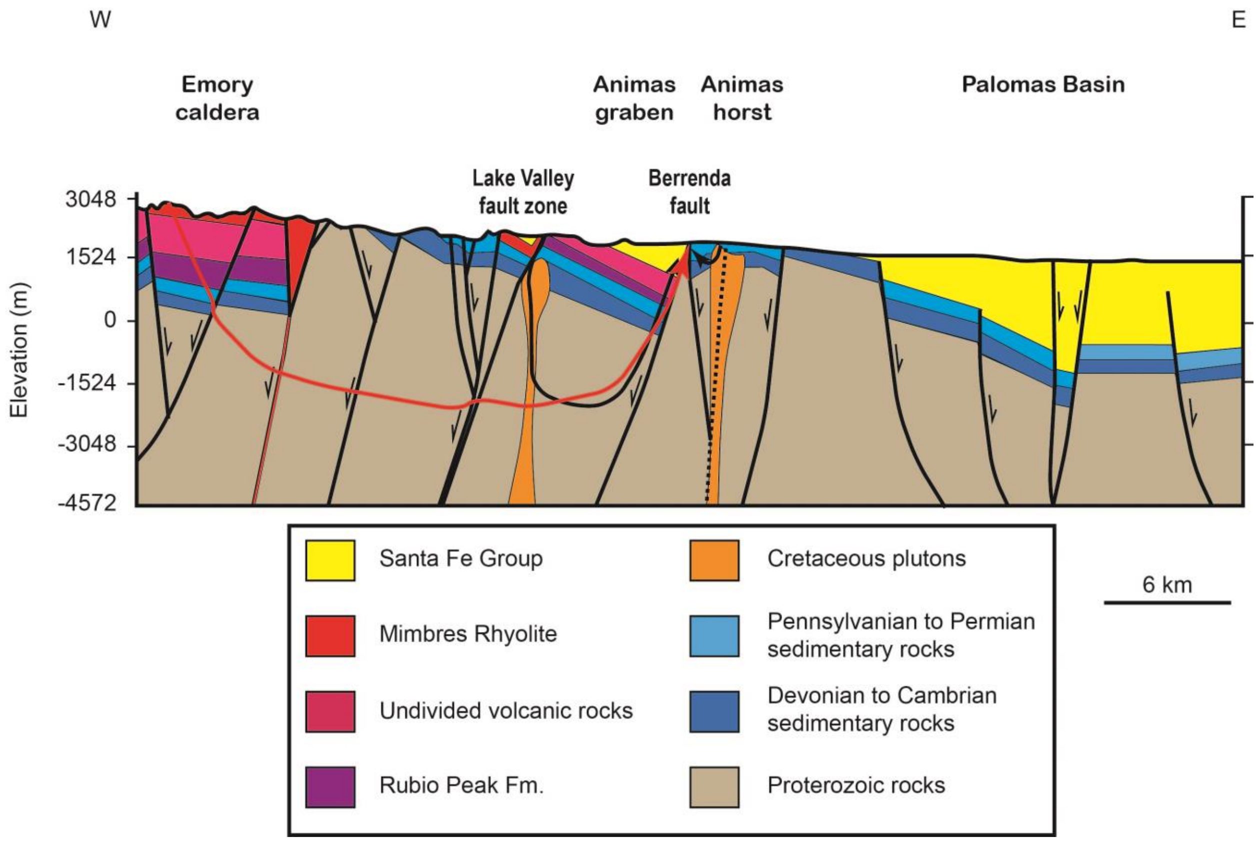

Figure 3. Cross-section through Hillsboro area structures and strata. Section is through Animas graben and horst in the northern part of the quadrangle. Red and black lines with arrows illustrate fluid flow and discharge at surface along Berrenda fault. From Kelley et al. (2014), using the map of Seager et al. (1982).

Laramide compression was followed by slab roll-back and voluminous eruptions in the Mogollon-Datil volcanic field starting at ~37 Ma (Seager et al., 1986; O'Neill et al., 2002; Chapin et al., 2004). The ~35.3 Ma Emory caldera formed during this event, producing the regionally extensive Kneeling Nun Tuff (McIntosh et al., 1991). The ~34.3 Ma Mimbres Peak Formation subsequently filled the ring fractures of the caldera.

GEOCHRONOLOGY

Several geochronologic studies provide critical ages for understanding both Eocene-Oligocene volcanic systems and the late Cretaceous evolution of Copper Flat. Summary geochronologic data for rocks dated within the Hillsboro quadrangle are given in Table 1. In addition to the Pliocene basalt samples dated by Seager et al. (1984), four basalt samples collected during the course of mapping were submitted for $^{40}A/^{39}A$ analysis. These include two samples collected from basalt flows on either side of Warm Springs Canyon and two samples from basalt flows exposed south of Percha Creek narrows. We also submitted a sample of fine-grained ash interbedded in Santa Fe Group gravel beds for $^{40}Ar/^{39}Ar$ geochronology. These ages should resolve the timing of the eruption of basalt flows on the west side of the Animas graben and those closer to the town of Hillsboro, as well as the age of early Santa Fe Group gravels onlapping volcanic bedrock in the western Animas graben. The discussion of these relationships therefore remains speculative in this report.

McIntosh and others (1991) provided $^{40}Ar/^{39}Ar$ ages for a series of upper Eocene-lower Oligocene ignimbrites. Among units exposed in or near the Hillsboro quadrangle, these include the Sugarlump Tuff (35.63 ± 0.15 Ma), the Kneeling Nun Tuff (35.34 ± 0.10 Ma), and the Caballo Blanco Rhyolite Tuff (32.06 ± 0.12 Ma). Note that these ages are scaled upward by 1.3% in this report to account for a revised sanidine monitor age of 28.201 Ma for the Fish Canyon Tuff advocated by Kuiper et al. (2008). O'Neill et al. (2002) provided ages of 34.32 ± 0.11 and 34.22 ± 0.16 Ma for the Mimbres Peak Formation rhyolite. Underlying all of these units is the Rubio Peak Formation**,** with a host of radiometric ages placing its deposition at middle to late Eocene (Loring and Loring, 1980; Clemons, 1982; Seager, 1986; McIntosh et al., 1991; O'Neill et al., 2002; McMillan, 2004).

Additional geochronology was conducted by McLemore and others (1999) on andesite flows and monzonite porphyries of Copper Flat (Table 1). These ages (~75 Ma) may also indicate the general age of karst fill observed in lower Paleozoic strata. If karst fill rocks are indeed related to fracturing and alteration associated with the development of the Copper Flat plutons, they signify pervasive collapse of Paleozoic strata during the late Cretaceous.

Finally, apatite fission-track ages for Cretaceous units at Copper Flat and near Trujillo Creek were obtained by Kelley and Chapin (1997). These ages contain significant implications for the timing of volcanism and uplift/erosion during the late Cretaceous and Tertiary that are discussed in the report.

Table 1. Summary geochronology for rocks dated in the Hillsboro quadrangle.

Unit	Map symbol	Method	Age (Ma)		2σ error	Brief description	Reference
Basalt	Tb	^{40}K/^{40}A	4.2	±	0.1	Lowest of 3 flows overlying QTp and Tsf gravels.	Seager et al. (1984)
Older basaltic andesite	Tba$_1$	^{40}K/^{40}A	28.1	±	0.6	Intermediate-composition flows unconformably overlain by Tsf fanglomerate.	do.
Trujillo Creek intrusives	Kit	AFT[a]	63.7	±	4.5[b]	Intermediate-composition, porphyritic intrusives.	Kelley and Chapin (1997)
Warms Springs porphyry	Kwsm	^{40}A/^{39}A	74.4	±	2.6	Porphyritic, equigranular quartz monzonite.	McLemore et al. (1999)
Copper Flat porphyry	Kcpm	^{40}A/^{39}A	74.93	±	0.66	do.	do.
do.	do.	AFT[a]	21.7	±	3.6[b]	do.	Kelley and Chapin (1997)
Andesite of Copper Flat	Ka	^{40}A/^{39}A	75.4	±	3.5	Porphyritic-aphanitic to porphyritic andesite.	McLemore et al. (1999)

[a] AFT = apatite fission-track.
[b] 1σ error.

PRECAMBRIAN ROCKS

Precambrian rocks are only sparingly exposed in the Hillsboro quadrangle. They consist of unfoliated granite (pЄg) exposed southwest of Copper Flat and foliated, quartzofeldspathic gneiss (pЄs) exposed along Tank Canyon to its northwest (Hedlund, 1977). The lack of deformation fabric in the relatively coarse-grained granite may suggest anorogenic emplacement, whereas the well-defined foliation of the gneiss implies that it was deformed. Amato and Becker (2012) dated granophyric granite from near Kingston (~10 km west of Hillsboro) at 1655 ± 15 Ma (U-Pb). Although it is uncertain whether the Tank Canyon gneiss has a similar age, this date confirms that pre- and/or syn-orogenic rocks related to the ~1.65 Ga Mazatzal orogeny are locally present (Amato et al., 2008).

PALEOZOIC ROCKS

Paleozoic strata near Hillsboro are commonly deformed and/or altered as a result of pervasive faulting and/or fluid interaction during late Cretaceous volcanism and the emplacement of the Copper Flat area porphyries. To a lesser extent, deformation of Paleozoic rocks may be attributed to paleokarstification, particularly in the Montoya Formation (O'Neill et al., 2002; Seager and Mack, 2003). As a result of collapse and/or alteration, contacts between Paleozoic strata are typically less clear in the Hillsboro area than they are in the Caballo Mountains and elsewhere in southern New Mexico. Where they can be delineated, disconformities between units likely represent regressive events, characterized by non-deposition and/or erosion. Although the lower to middle Paleozoic rock record in southern New Mexico is commonly tied to eustatic changes in sea level, transgressive-regressive cycles may also have been influenced by epeirogenic events causing inundation along the continental margin (e.g. Pysklywec and Mitrovica, 1998).

Lower to middle Paleozoic rocks in the Hillsboro area were deposited on a stable, epicratonal shelf with low rates of sedimentation and subsidence, and periodic inundation by shallow, tropical seas (Seager and Mack, 2003). The oldest Paleozoic strata exposed near Hillsboro (and throughout southern New Mexico and west Texas) is the Cambro-Ordovician Bliss Formation (**ЄOb**). This unit consists of dark, cross-laminated, quartzose sandstone exposed north and south of Copper Flat that is locally metamorphosed to quartzite, and is the basal unit of an early eastward and northward transgression (Mack, 2004). This fine-grained sandstone is interpreted as an upper to middle shoreface storm deposit based on the presence of vertical burrows (probably *Skolithos*) and laminae. Above a gradational contact with the Bliss Formation lies cherty limestone to limey mudstone of the El Paso Group (**Oep**), best exposed in Percha Creek Box, sec. 14, T16S, R7W. Some facies feature laminated chert (Figure 4A), while other beds contain a diverse faunal assemblage of gastropods (Figure 4B), small bryozoans, horn coral, and stromatolites, as well as common horizontal bioturbation. The El Paso Formation was deposited on a shallow-marine shelf below wave base (Seager and Mack, 2003), and represents as many as five transgressive-regressive events (Mack, 2004).

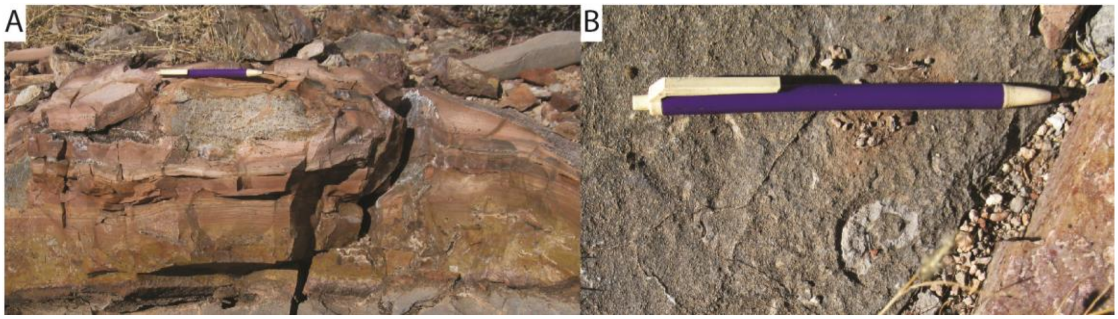

Figure 4. The El Paso Formation (**Oep**). (A) Laminated chert. (B) Gastropod.

The middle to upper Ordovician Montoya Formation (**Om**) in the Hillsboro area consists of the Cable Canyon Sandstone, a poorly-sorted quartz arenite, and non- or sparsely fossiliferous dolostone. The best exposures are in and near Percha Creek Box, where the Cable Canyon Sandstone forms a prominent marker bed (Figure 5). The Montoya Formation lies disconformably above the El Paso Formation. The Cable Canyon Sandstone has been interpreted as shallow-marine sand ledges formed from sand dunes reworked during a transgressive event (Bruno and Chafetz, 1988; Pope, 2004). However, the relative angularity of grains in the sandstone exposed near Hillsboro could imply deposition near the upper shoreface or foreshore. Sparsely fossiliferous dolostone beds of the Montoya were likely deposited in deeper water, and Pope (2004) suggests that cherty intervals may indicate upwelling associated with late Ordovician glaciation. Beds with corals perhaps imply occasional shoaling and/or deposition on a warm-water ramp.

The lower to middle Silurian Fusselman Dolomite (**Sf**) lies above a sharp disconformity with the Montoya Formation, and consists of cherty, dolomitic wackestone. It is exposed near Percha Creek Box but is considerably less altered to the south near Trujillo Creek. Though typically fossil-poor, it may locally contain silicified brachiopods. The sedimentary fabric of the Fusselman is typically obscured by dolomitization, hindering interpretation of its depositional environment. However, Pope (2004) suggests that it was deposited on a warm-water carbonate ramp based on peritidal mudstone and subtidal, coral-rich wackestone/packstone. Brecciated jasperoid beds near the top of the Fusselman may be associated with slippage along its contact with the ductile Percha Shale, forming a cap to fluid migration (O'Neill et al., 2002).

Figure 5. Cable Canyon Sandstone. This unit is found at or near the base of the Montoya Formation (**Om**) and forms a prominent marker bed in the Percha Creek Box area.

The Percha Shale (**Dp**) unconformably overlies the Fusselman Dolomite, and is exposed throughout the Animas Hills where it underlies steep slopes or valleys. It typically consists of dark colored, calcareous shale overlain by or interbedding with fossiliferous shale and siltstone with common limestone nodules. O'Neill and others (2002) designated these facies as the Ready Pay and Box members, respectively, though these members are not individually mapped in the Hillsboro quadrangle. The lower shaly interval was probably deposited in an oxygen-poor environment well below wave base. Fossils in the upper, silty shale to siltstone include the brachiopods *Schizophoria australis* and *Petrocrania* sp. (B.S. Kues, personal comm., 2014). This interval was likely deposited by stronger currents near normal wave base (Seager and Mack, 2003).

Mississippian strata of the Hillsboro quadrangle include the Caballero Formation (**Mc**) and the Lake Valley Limestone (**Mlv**). The former is comprised of massive to cross-stratified, cherty, fossiliferous limestone. The latter includes limestone with abundant marine invertebrate fossils, and subordinate siltstone and mudstone. Both formations are exposed throughout the Animas Hills, but the Caballero Formation appears to pinch out north of Trujillo Creek. In the southeastern part of the quadrangle, the Nunn Member of the Lake Valley Limestone (**Mlvn**) is easily identified by its distinctive crinoid hash. Lake Valley deposition took place on a shallow-marine ramp in warm, oxygen-rich water (Seager and Mack, 2003). Late Mississippian to early Pennsylvanian erosion accounts for variable thickness of the Lake Valley Limestone; the unit at Hillsboro is generally over 3x thicker than its counterpart in the southern Caballo Mountains.

Pervasive deformation and alteration of Pennsylvanian rocks precludes subdivision of the Magdalena Group (**ℙm**) into its formation-rank members in the Hillsboro quadrangle. However, lower Pennsylvanian rocks lying disconformably above the Mississippian Lake Valley Limestone north of Trujillo Creek likely belong to the Morrowan-Atokan Red House Formation, though they lack tidal-fluvial sandstones and conglomerates observed elsewhere (e.g. Lucas et al., 2012). In general, the deposition of Magdalena Group strata coincides with the ancestral Rocky Mountain orogeny, beginning during the latest Morrowan to Atokan (Kues and Giles, 2004). Among the early events of this orogeny were uplift and erosion of the Pedernal uplift to the east and transgression throughout the state (Ye et al., 1996). Rare siliciclastic facies in the Magdalena Group (primarily siltstone in the Hillsboro area) may have been sourced from the Pedernal uplift and perhaps more proximal highlands. Transgression reached a maximum during the Desmoinesian age, resulting in deposition of limestones of the Nakaye Formation in a slowly subsiding basin (Kues and Giles, 2004). Subsequent Desmoinesian-Missourian glacio-eustastic cyclicity may account for shale-rich strata of the Bar B Formation (upper part of the Magdalena Group) in the nearby Caballo Mountains (Soreghan, 1994). However, neither cliff-forming limestone of the Nakaye nor abundant shale intervals of the Bar B are clearly exposed near Hillsboro, implying that these formations are locally absent or, more likely, deformed and lacking their typical topographic expressions (e.g. Lucas et al., 2012). Fossils recovered from Magdalena Group limestones near the Percha Creek Box include the brachiopods *Linoproductus* sp. and *Derbyia* sp. (B.S. Kues, personal comm., 2014).

CRETACEOUS HISTORY OF COPPER FLAT

Like other porphyry copper deposits in the southwest, the formation of Copper Flat and its associated volcanic facies is related to the Laramide orogeny, with source magma generated above the subducting Farallon plate beginning ~75 Ma (Keith and Swan, 1996; McLemore et al., 2000). The resulting volcanic system exhibits a strong alkalic affinity, distinct from other volcanic suites in southern New Mexico (McMillan, 2004). Previous mappers focused on mapping dikes and associated vein ores that intrude late Cretaceous volcanic and volcaniclastic rocks and generally form radial patterns around the Copper Flat stock. Our mapping involved a concerted effort to delineate flows of differing mineralogy and their approximate age relationships on the south and east sides of Copper Flat. The northwest corner of Copper Flat is mapped as undivided andesite due to restricted land access.

Andesite and laharic breccia of Copper Flat were deposited on the flanks of a stratovolcano ~75 Ma (Seager, 1986; McLemore et al., 2000). In total, seven distinct volcanic or volcaniclastic facies were mapped. The most prominent of these is laharic flow breccia (**Kab**), typically consisting of matrix-supported, massive breccia with pebble- to cobble-sized fragments of non-vesicular andesite (Figure 6A). However, large boulders (Figure 6B) to blocks of andesite 10s of meters across may be found. Rarely, the breccia interbeds with altered, tabular sandstone (Figure 6C). Clasts in the breccia consist of a variety of andesitic lithologies, in some places dominated by plagioclase-phyric andesite while in others by potassium feldspar-phyric andesite. These clast lithologic distributions are discrete, implying multiple generations of breccia deposition. Distinct, greenish gray debris flows (**Kvs**) with altered clasts are found in Wicks Gulch (Figure 6D). In general, breccia deposition seems to span nearly the entire interval over which Copper Flat volcanic facies were formed.

Figure 6. Laharic breccia and volcaniclastic gravel of Copper Flat. Hammer is ~30 cm long. (A) Typical matrix-supported pebble-cobble breccia (**Kab**). (B) Boulder in laharic breccia (**Kab**). (C) Tabular sandstone interbedded with breccia (**Kab**). (D) Pebble breccia of Wicks Gulch (**Kvs**).

Andesitic facies of Copper Flat include varieties rich in hornblende (**Kah**), potassium-feldspar (**Kaf**), plagioclase (**Kap**), and pyroxene (**Kax**) phenocrysts. Feldspar-phyric flows are the most widely distributed of these and are probably of an intermediate age compared to the other flows. Plagioclase-phyric lava caps high ridges and peaks of potassium feldspar-phyric flows or breccia, including Animas Peak. A single pyroxene-phyric flow underlies the Tertiary basalt forming Black Peak. These two units are interpreted as the youngest andesites at Copper Flat. Hedlund (1977) estimates the composite thickness of Copper Flat andesite and breccia at ~830 m.

Two episodes of pluton emplacement post-date andesite eruptions and breccia deposition. The Copper Flat quartz monzonite (**Kcpm**) comprises the older stock, dated at ~74.9 Ma (Table 1; McLemore et al., 1999). This medium-grained monzonite contains quartz and plagioclase, as well as local deposits of pyrite, chalcopyrite, and molybdenite associated with hydrothermal alteration (McLemore et al., 2000). The Warm Springs quartz monzonite (**Kwsm**) is similar, but largely unaltered where it intrudes late

Cretaceous andesite and Paleozoic strata on the south side of Copper Flat. It is dated at ~74.4 Ma (Table 1; McLemore et al., 1999). Pervasive hydrothermal alteration of the Copper Flat quartz monzonite as well as the andesite and breccia intruded by the monzonite resulted in rich metal deposits mined since the late 19th century.

Dikes, sills, and plugs intrude all volcanic strata at Copper Flat, as well as both porphyries and Paleozoic strata. McLemore and others (2000) identified 34 radial dikes, commonly paralleled by polymetallic veins, in the Copper Flat area. There are many smaller dikes that exhibit a variety of cross-cutting relationships, often obscuring the sequence in which dikes intruded older facies. Dikes are commonly intermediate in composition (**Ki**), often with conspicuous plagioclase phenocrysts. Other dikes may be rich in biotite (**Kib**) or potassium feldspar (**Kif**). Potassium feldspar-phyric dikes may be among the oldest based on cross-cutting relationships with intermediate composition dikes. Small plugs are also present, including a rhyolitic plug (**Kir**) near Animas Gulch that is thought to be younger than other intrusive bodies. Other non-tabular intrusive bodies include gabbroic (**Kig**) to monzonitic (**Kim**) plugs north of Copper Flat, and a single outcrop of basaltic (but olivine-poor) composition west of Black Peak (**Kb**).

Near Trujillo Creek, intrusive andesite (**Kit**) has an apatite fission-track (AFT) age of ~64 Ma (Table 1; Kelley and Chapin, 1997). Clasts of this intrusive body have been recovered in the upper Cretaceous-Paleocene(?) McRae Formation and the Paleocene(?)-Eocene Love Ranch Formation near the Caballo Mountains, implying that an extensive sequence of volcanic and intrusive rocks related to the Copper Flat stratovolcano once blanketed the landscape far to the east (Seager and Mack, 2003). Thus, the intrusive andesite of Trujillo Creek may have been locally exposed on a bedrock high during the early Tertiary, whereas AFT data for the Copper Flat porphyry suggest that it remained buried until the late Oligocene/early Miocene (Kelley and Chapin, 1997).

Some of the most distinctive features that may be late Cretaceous in age are karst fill deposits (**LPzkf**) filled by fragments to blocks of upper Paleozoic limestone and siltstone in a reddish, silty matrix intermixed with pervasively deformed Percha Shale (Figure 7A). Blocks may be up to 10s of meters across and include Pennsylvanian Magdalena Group limestone based on the identification of several brachiopod genera;

Lake Valley Limestone is likely also present. Red siltstone fragments appear to belong to the Permian Abo Formation, though it is not currently exposed in the quadrangle. We suggest that these deposits are coeval with the evolution of the Copper Flat volcanic system. In particular, the emplacement of the Copper Flat stock may have resulted in the circulation of sulfate-rich water. This acidic fluid would have penetrated fractures surrounding the stock and stratovolcano, eventually resulting in dissolution of susceptible facies such as lower Paleozoic limestone.

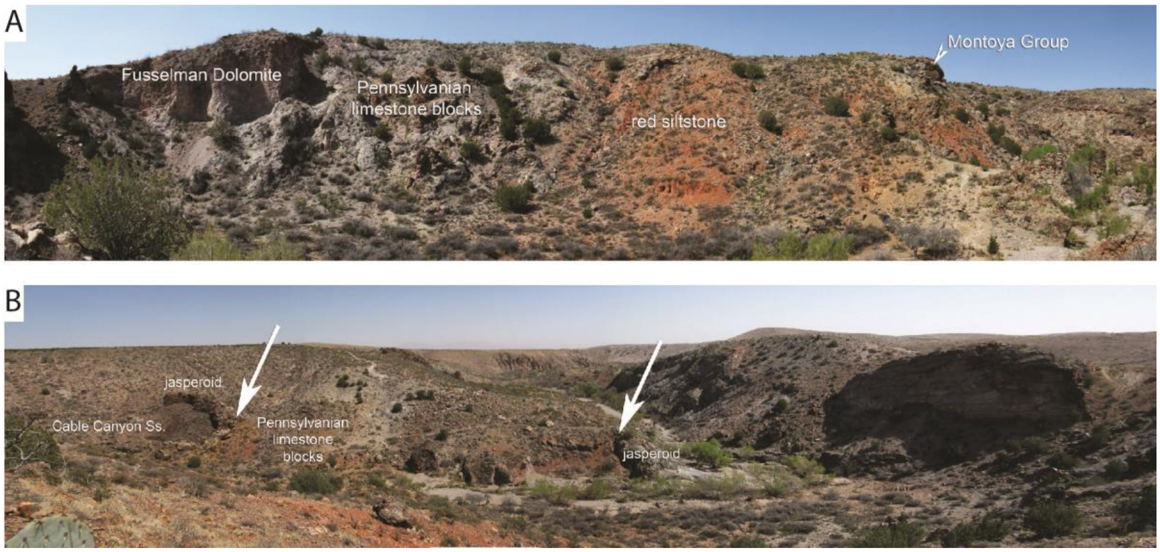

Figure 7. Karst fill of late Paleozoic rocks (**LPzkf**). (A) View looking west (upstream) toward Percha Creek Box. Note in-place Fusselman Dolomite and Montoya Group. (B) View looking east (downstream) away from Percha Creek Box. Strata-bound jasperoids (white arrows) border a collapse feature, and were likely formed by early infiltration of sulfate-rich groundwater and dissolution prior to sinkhole collapse.

Three generations of karst formation were identified based on mapped relationships. The older episode affected the El Paso Formation and may be Ordovician in age. One karst deposit just south of the Warm Springs pluton incorporates only El Paso limestones, and contains just a trace of reddish alteration. The second generation of karstification began with widespread dissolution of the Montoya Formation just above the Cable Canyon Sandstone. This episode resulted in the formation of chert-bearing jasperoid common south of Copper Flat. The final stage cut across the Cable Canyon Sandstone and the strata-bound jasperoid chert breccia formed in the second stage (Figure 7B). Percha Shale, Lake Valley Limestone, Pennsylvanian limestone, and Abo siltstone are recognizable units that collapsed into sinkholes. This final episode of dissolution is not mineralized.

Additional, but distinct, alteration of Paleozoic country rock occurs in the form of alteration to jasper or metamorphosis to skarn or marble north and south of Copper Flat. McLemore et al. (2000) constrained this later episode of hydrothermal alteration to ~75-35 Ma, based on the contact between altered Fusselman Dolomite and overlying, unaltered Sugarlump Tuff.

EOCENE-OLIGOCENE VOLCANISM AND RIO GRANDE RIFT EXTENSION

Tertiary volcanic rocks exposed along the eastern flank of the Black Range record the transition from arc-style magmatism to rift-related volcanism. Late Cretaceous to Eocene magmas of the Hillsboro region tend to vary in their alkalinity and are commonly transitional between calc-alkaline and tholeiitic affinities (McMillan, 2004). Arc-style volcanism gave way to slab roll-back related volcanism of the Mogollon-Datil volcanic field, including large ignimbrite eruptions and later calc-alkalic volcanism during Rio Grande rift extension (Seager et al., 1984; Chapin et al., 2004). Mack and others (1994) suggested that there were four major episodes of rifting, with volcanic strata exposed near Hillsboro corresponding to the earlier two phases beginning ~35 Ma and during the late Oligocene.

The Rubio Peak Formation (**Trp**) is the oldest Tertiary volcanic/volcaniclastic unit exposed in the Hillsboro quadrangle and consists of volcaniclastic sandstone and siltstone interbedded with plagioclase-phyric andesite. The formation typically underlies gentle to moderate slopes, and may include large, exotic blocks of Pennsylvanian limestone transported during laharic debris flows. One such block is observed on the west side of Trujillo Park Canyon. Ages for the Rubio Peak Formation range from 46.3 to 36.7 Ma, including both lava flows and older clasts found in laharic breccia (Loring and Loring, 1980; Clemons, 1982; McMillan, 2004).

Deposition of the Rubio Peak Formation was succeeded by large-scale eruption of ignimbrites and rhyolite. In the Hillsboro area, these volcanic facies were mostly sourced from the 35.3 Ma Emory caldera to the west (Figure 2), although the 35.6 Ma Sugarlump Tuff (**Ts**) is not regionally extensive and may have been sourced from a more distant caldera (McIntosh et al., 1991; Chapin et al., 2004). The 35.3 Ma Kneeling Nun Tuff (**Tkn**) is well exposed in this part of the southern Rio Grande rift (McIntosh et al., 1991), and is typified by dense welding and high phenocryst content. The ~34.3 Ma Mimbres Peak Formation rhyolite (**Tmr**) filled in the ring fractures of the Emory caldera after eruption of the Kneeling Nun. Several million years of volcanic history are missing between it and the 32.1 Ma Caballo Blanco Rhyolite Tuff (**Tcb**), thought to have erupted from the Twin Sisters caldera ~40 km to the west (McIntosh et al., 1991; Chapin et al., 2004). Upper Eocene volcanic strata are well exposed in Trujillo Park Canyon (Figure 8).

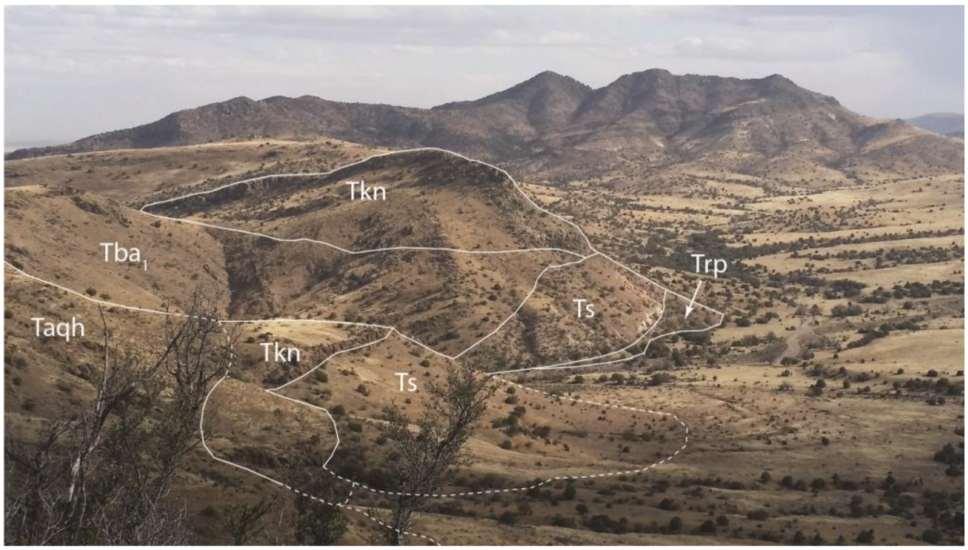

Figure 8. Volcanic stratigraphy in Trujillo Park Canyon. View is toward the south. McClede Mountain forms the skyline and is comprised of the Mimbres Peak Formation (**Tmr**), including rhyolite sparingly exposed in the western Hillsboro quadrangle.

Lacustrine sediment (**Tss**) exposed near the Percha Creek narrows (sec. 18, T16S, R7W; sec. 13, T16S, R7½W) overlies (and perhaps interbeds with) the Caballo Blanco Rhyolite Tuff just off the western edge of the quadrangle (Seager, 1986); a typical outcrop is shown in Figure 9. The lake in which this sediment was deposited appears to have eventually spilled over one or more constrictions, with fine-grained sandstone and siltstone grading upward into pebbly sandstone and conglomerate signifying a transition to fluvial deposition. The unit also interfingers with older basaltic andesite (**Tba$_1$**) dated at ~28 Ma (Seager et al., 1984). Elsewhere, lacustrine sediment underlies younger basaltic andesite (**Tba$_2$**; Figure 10).

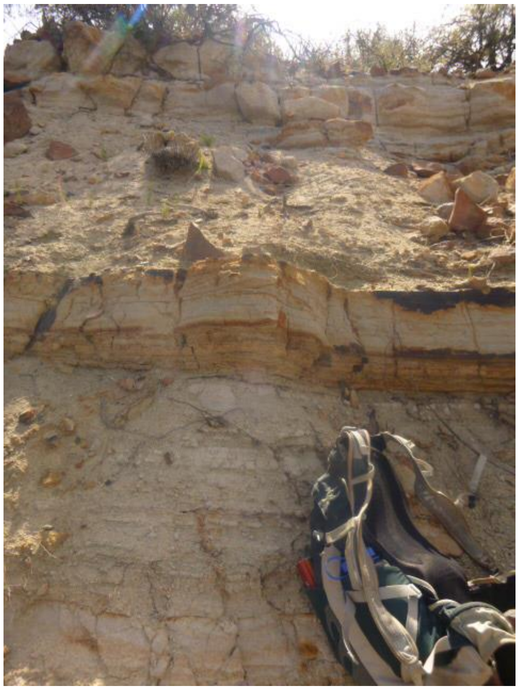

Figure 9. Laminated lacustrine sediment (**Tss**) west of Percha Creek narrows. Note iron oxide staining along laminae, as well as concretion in upper part of central sandstone bed. Slopes are underlain by less resistant siltstone. Pack is approximately 0.6 m tall.

Deposition of the older basaltic andesite was followed by a significant succession of late Oligocene volcanism that resulted in several andesites with variable phenocryst content (**Taqh**, **Ta**, **Tba**$_2$), and a transition to silicic volcanism forming rhyolite (**Tr**), dacite (**Td**), and tuffaceous volcaniclastic sediment found in Tank Canyon (**Tttc**). The latter unit commonly features reworked ash beds and pumice (Figure 11). Volcaniclastic beds (**Tvs**) distinct from those of the Rubio Peak Formation are mapped near Percha Creek Box and underlying Pliocene (?) basalt in the western part of the quadrangle. These debris flows typically lack stratigraphic context, but may span the late Eocene to upper Oligocene. Finally, the andesite of Trujillo Peak (**Tat**) appears distinct from the volcanic units in the western part of the quadrangle, although it may correlate to the middle and upper beds of the younger basaltic andesite (**Tba**$_2$) based on generally low phenocryst content and variable foliation and vesicularity. These flows lie unconformably above a small exposure of Kneeling Nun Tuff, and O'Neill and others (2002) considered their correlative flows to the south to be ―middle" Oligocene in age.

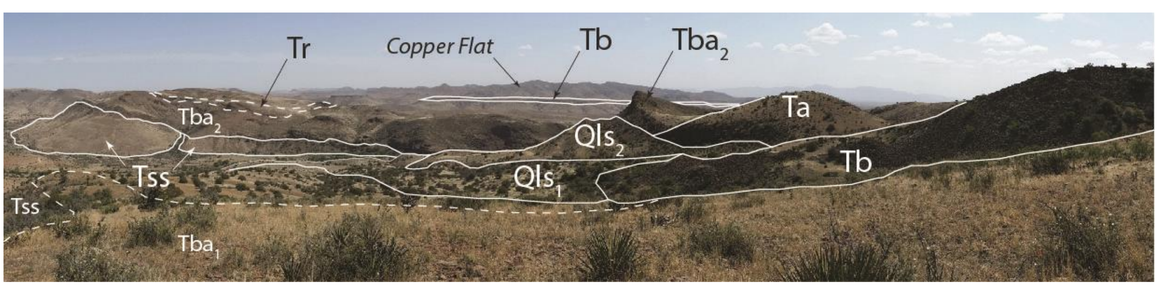

Figure 10. Volcanic facies and landslides exposed west of the Percha Creek narrows (westernmost part of quadrangle). View is toward the northeast. Landslide material rests on weak lacustrine sediment (**Tss**).

Figure 11. Tuffaceous sediment of Tank Canyon (**Tttc**).

The Thurman Formation (**Tt**) is exposed only in the southwestern corner of the quadrangle, where it consists of sandstone draped on dacite (**Td**) and quartz-hornblende andesite (**Taqh**). O'Neill et al. (2002) mapped similar, lenticular bodies of the Thurman Formation to the south. Elsewhere, the dominantly fine-grained deposit contains fallout tephra dated at 27.4 Ma, implying that the Thurman was deposited on a volcaniclastic apron of the Mount Withington caldera some 115 km to the north (McIntosh et al., 1991; Seager and Mack, 2003). Broad cross-stratification and the presence of pebble-rich conglomerate in the exposures near Trujillo Creek indicate deposition by sheetflooding.

QUATERNARY-TERTIARY BASIN-FILL

Basin-fill in the western Palomas Basin (eastern part of the Hillsboro quadrangle) has been variably mapped as mostly Quaternary fan gravels (Hedlund, 1977), entirely Plio-Pleistocene Palomas Formation fanglomerates (Seager et al., 1982), or Palomas fanglomerate buttressed against Miocene-Pliocene gravel/conglomerate of the Santa Fe Group (Seager, 1986). Our mapping revealed mostly Santa Fe Group basin-fill in the eastern part of the quadrangle, but its buttress unconformity with younger Palomas gravels is well-exposed along both Grayback Arroyo and Wicks Gulch east and southeast of Copper Flat.

The Santa Fe Group (**Tsf**) in the study area is likely correlative to the Hayner Ranch Formation, the lowermost unit of the Santa Fe Group in the Palomas and Rincon basins to the east and southeast, respectively. Although the upper Miocene-lower Pliocene Rincon Valley Formation is known to contain basin-margin fanglomerates (Hawley et al., 1969; Seager et al., 1971), we suggest that the Santa Fe Group gravels exposed in the Hillsboro quadrangle were deposited in an early rift basin (i.e. the Animas graben) bound by the Berrenda fault. This fault offsets Eocene volcanic and volcaniclastic rocks in the region, and would have generated sufficient accommodation space for early rift-margin alluvial fan deposits.

The most common lithologies of the Santa Fe Group in the Hillsboro quadrangle are pebbly sand/sandstone beds and pebble-cobble gravel/conglomerate. The matrix-supported, typically massive nature of these beds suggests proximal deposition on large alluvial fans emanating from the west. Deposition was mostly via debris flows, but occasional cross-stratified beds with lenticular bodies of pebble-cobble gravel represent local inter- or extra-channel deposits. Paleocurrent determined from clast imbrication is generally eastward in older Santa Fe Group beds, but may be toward the south in younger beds. This shift could be due to drainage reorganization in coalescing fans, or alternatively, a response to faulting and attendant drainage capture on the Berrenda fault zone, temporarily focusing flow into the subsiding Animas graben. The Santa Fe Group is generally finer-grained in the eastern part of the Hillsboro quadrangle, representing a transition to medial fan facies, and commonly silicified in and around fault zones. Although only ~200 m of Santa Fe Group gravels are exposed at the surface, the eastern boundary of the Animas graben along Copper Flat may preserve a thickness of up to ~500 m.

The contact between older Santa Fe Group beds and the overlying Plio-Pleistocene Palomas Formation (**QTp**) is typically an abrupt buttress unconformity, marked by an increase in average clast size and more consistent cementation in the younger gravels. Palomas deposits are dominated by sandy pebble-cobble-boulder conglomerate with subordinate pebbly sand/sandstone. In Wicks Gulch, imbricated clasts suggest an average paleocurrent toward the east-southeast; paleocurrent measurements throughout the Palomas Basin are typically perpendicular to the margins of the basin, implying that modern drainage configurations have perhaps remained largely unchanged since the Pliocene. The Palomas Formation underlying the ~4.2 Ma basalt of Warm Springs Canyon is < 10 m thick, but the formation thickens rapidly east of Copper Flat to a minimum of 90-100 m near the town of Caballo (Seager and Mack, 2005).

Miocene-Pliocene basin-fill contains scarce clasts of Paleozoic carbonate and siliciclastic lithologies, whereas these lithologies are more common (up to 20% of clasts) in Quaternary stream gravel. This common clastic make-up of older fan gravels versus Quaternary axial stream deposits likely reflects very recent incision into Paleozoic strata on the eastern face of the Black Range. Despite several uplift events associated with the evolution of the Rio Grande rift, thick sequences of Eocene-Oligocene volcanic deposits have protected Paleozoic rocks from incision until rather recently, perhaps as late as the early-middle Pleistocene.

PLIOCENE BASALT

Pliocene basalt (**Tb**) is found at several locations in the Hillsboro quadrangle, and several other mesa-capping flows are postulated to be Pliocene in age based on their landscape position and mineralogic character. In Warm Springs Canyon, a basalt flow overlying undeformed gravels of the Palomas Formation and slightly tilted Santa Fe Group fanglomerate was dated by Seager and others (1984) at ~4.2 Ma (Table 1). They also dated basalt flows just east of the quadrangle at ~4.5 Ma; these flows were presumably sourced from the ‗Vulcan' vent found in the northeast corner of the quadrangle. Red cinder deposits at the base of the basalt flow on Black Peak are ~1 m thick on the south side of the exposure and 10 m thick on the north side, suggesting a local vent and lava that flowed toward the northeast, filling a paleovalley with a floor that is only 24 m above modern stream grade.

Late Miocene to Pliocene and Quaternary basalt flows in the southern Rio Grande rift are generally alkali-olivine, in contrast to the calc-alkaline suite of Oligocene volcanic strata. The younger basalts are thought to be related to renewed extension following a period of relative quiescence (Seager et al., 1984; Mack et al., 1994).

QUATERNARY HISTORY

Pleistocene-Holocene terrace deposits of Percha Creek and its tributaries and landslide deposits in the central and western parts of the map area are the most notable late Quaternary deposits of the Hillsboro quadrangle. Though subordinate to these units, piedmont deposits present as thin gravel veneers provide important benchmarks in the landscape for at least two previous erosional surfaces. Terrace and fan levels distributed throughout the local landscape argue for as many as four episodes of entrenchment and aggradation since the middle (?) Pleistocene.

Episodes of stream terrace aggradation are likely related to middle and late Pleistocene (as well as Holocene) climatic events. No offset is observed where these deposits span major structures, negating a tectonic control on terrace formation. The four terraces of Percha Creek may correspond to glacial-interglacial cycles during the middle to late Pleistocene, but age control is lacking in this part of the Rio Grande rift. However, one model proposes that incision occurs in the Rio Grande and the lower valleys of its tributaries during full glacial conditions, aggradation occurs during the transition to interglacial intervals due to decreased water to sediment ratios, and stability ensues for the remainder of the interglacial interval (Gile et al., 1981). This model may suggest that the four terraces of Percha Creek correspond to glacial-interglacial transitions occurring during marine isotope stages (MIS) 14-13 (**Qao_0**), MIS 12-11 (**Qao_1**), MIS 10-9 (**Qao_2**), and MIS 6-5 (**Qao_3**), but these ages are speculative in the Hillsboro area. Each of the three younger terraces is sometimes associated with a fan prograded to its surface (implying initial deposition after the aggradation of terrace deposits had begun), and this relationship is observed in Holocene deposits as well (**Qay** and **Qah**).

Landslides are observed at multiple locations and scales in the central and western Hillsboro quadrangle, typically on weak substrate of the Santa Fe Group or Oligocene lacustrine sediment. At least two generations of mass movement are found west of Percha Creek narrows (Figure 10), where a younger, smaller slide (**Qls_2**) rests atop an older slide (**Qls_1**). These deposits feature hummocky surface textures and contain distinct toes and lobes of open-framework gravel. The younger deposit contains a large (≤ 100 m across), detached block of younger basaltic andesite (**Ta**) near its headscarp, and the older deposit features several blocks of chaotically deformed andesite. These deposits appear translational in nature, likely failing on steep slopes of Tertiary lacustrine sediment during unusually wet periods of the middle to late Pleistocene.

Lacustrine deposits (**Ql**) along Trujillo Creek suggest possible damming during the Holocene, perhaps in the bedrock canyon below Trujillo Peak. Alternatively, backfilling of the low-lying Trujillo Creek valley due to low stream gradient and poor drainage integration downstream could have resulted in temporary ponding. In either event, the result was the deposition of fine-grained, laminated sediment ≥ 6-9 m thick over an area of ~0.7 km^2.

STRUCTURAL GEOLOGY

At least three episodes of post-Laramide faulting have been recognized in the Hillsboro area (O'Neill et al., 2002). The southern, NW-striking part of the Lake Valley fault (Figure 2) has a history of offset occurring prior to middle Cenozoic volcanism because this normal fault controls the distribution of the oldest Eocene lava flows in the area. The northern, N-striking portion of the Lake Valley fault is a ring fracture fault that formed during the collapse of the Emory caldera (Figure 2).

The Berrenda fault is part of the Rio Grande rift normal fault system. Generally, rock units displaced by the Berrenda fault dip 10 to 20° to the east (O'Neill et al., 2002), coinciding with the groundwater flow direction. The north and south splays of the Berrenda fault in the Lake Valley area have 360 m and < 250 m of dip-slip and right-slip, respectively. The north-striking Berrenda fault turns sharply toward the SW and breaks into two major splays south of Sibley Mountain (Figure 2). Basin-fill deposits of the Santa Fe Group are juxtaposed against Pennsylvanian limestone and shale along the Berrenda fault north of the bend; here the amount of displacement is not constrained (O'Neill et al. 2002). South of the bend, the main splay of the Berrenda fault has 600 m of down-to-the-NW displacement and the southern splay has 300 m of down-to-the-NW offset; slickenlines on both splays are primarily dip-slip (O'Neill et al., 2002). Along the west side of Copper Flat, the Berrenda fault displays nearly pure dip-slip displacement of more than 1600 m.

The two major fault zones (Berrenda and Lake Valley) cross each other along Berrenda Creek, south of the Hillsboro quadrangle. The origin of E-W striking faults in the Lake Valley and Berrenda Creek areas is uncertain (O'Neill et al., 2002); the faults roughly parallel the Laramide structures, but these faults offset units as young as the Eocene Rubio Peak Formation. Basaltic lava flows ~4.8 Ma in age are clearly faulted southwest of the Hillsboro quadrangle (Seager et al., 1982, 1984). Evidence for Pliocene slip on both the Berrenda and Lake Valley faults within the Hillsboro quadrangle includes offset observed in basalt flows southeast of Hillsboro and south of Percha Creek narrows. Pliocene offset on the Lake Valley fault appears limited to 6-7 m, but is uncertain on the Berrenda fault, where basalt flows abruptly terminate against Miocene-Pliocene Santa Fe Group conglomerate in the footwall that lack remnants of capping basalt. Although Quaternary faults are common in the Palomas Basin to the east, no Quaternary faults have been mapped in the Animas half-graben (Seager et al., 1982).

Of note is the fact that Paleozoic strata on the north and south sides of Copper Flat are typically not in fault contact with late Cretaceous volcanic rocks. Although these relationships have been mapped in the past, we observed little evidence for Cretaceous or younger faulting along these contacts. Instead, it seems that these unconformities resulted from doming around the stratovolcano prior to eruption.

A fold pair is observed south of the Percha Creek Box, deforming the Percha Shale and Lake Valley Limestone. Folding in the Caballo Mountains is typically Laramide in origin, but the Percha Creek Box folds are nearly perpendicular to the structural grain of the NW-trending Rio Grande uplift. An alternative explanation involves large-scale drag-folding initiated by slip along faults associated with the Berrenda fault, though it is difficult to reconcile this interpretation without invoking contemporaneous slip on an oppositely-dipping fault to the east of the folds. Such a fault does exist but its timing and displacement magnitude are unclear. For now, the origin of these structures remains unclear.

In addition to the major structures described above, numerous small faults penetrate the Santa Fe Group, and several structures were mapped offsetting andesite and breccia of Copper Flat. A small graben containing potassium feldspar-phyric andesite is observed just north of the Copper Flat mine and Animas Peak, but it is unclear whether these faults are related to rift extension.

HILLSBORO GEOTHERMAL POTENTIAL

Kelley et al. (2014) attribute the thermal waters in the Hillsboro area to the presence of deep circulation of groundwater that originated as precipitation in the Black Range and discharged along the Berrenda fault bounding the western part of the Animas horst (Figure 3). Reservoir temperatures predicted for chalcedony equilibrium points to thermal waters (82 to 137 °C). Furthermore, the K/Mg and Li/Mg geothermometers are 107 to 137°C for the Hillsboro warm springs and 82 to 137°C for other wells in the Hillsboro area. The hydrogeologic model predicts that the background heat flow in the area must be elevated (104 mW/m^2) to approach matching measured temperatures and the estimated geothermometry temperatures at Hillsboro. These heat flow values match the measured heat flow value at Lake Valley (Decker and Smithson, 1975). The predicted model heat flow value near Hillsboro is much higher than the measured heat flow value at nearby Copper Flat (Reiter et al., 1975), but the concave-up shape of the temperature logs at Copper Flat record show recharge on the Animas horst, which could mask the elevated regional heat flow.

APPENDIX: DETAILED UNIT DESCRIPTIONS

Introduction

The units described below were mapped using aerial photography coupled with delineation in the field. Stereogrammetry software (Stereo Analyst for ArcGIS 10.1, an ERDAS extension, version 11.06) permitted accurate placement of geologic contacts. Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Pebbles are subdivided as shown in Compton (1985). The term ―clast(s)” refers to the grain size fraction greater than 2 mm in diameter. Descriptions of bedding thickness follow Ingram (1954). Colors of sediment are based on visual comparison of dry samples to the Munsell Soil Color Charts (Munsell Color, 1994). 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). Description of sedimentary and igneous rocks was 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) can be used to differentiate stream terrace, alluvial fan, and valley floor deposits. Younger deposits are generally inset below older deposits; however, erosion may create a locally young surface on top of an older deposit, so Quaternary units were field-checked to identify this relationship.

Quaternary valley bottom units

daf Disturbed or artificial fill (present to ~50 years old) – Sand and gravel that has been moved by humans to form berms and dams, or has been removed for construction of infrastructure or buildings.

Qam Modern alluvium (present to ~50 years old) – Sandy gravel underlying ephemeral drainages. Deposit is unconsolidated, massive to cross-bedded, and occurs in lenticular beds. Gravel is commonly imbricated and consists of Tertiary volcanic and sedimentary lithologies, as well as Paleozoic carbonate sourced locally or in the Black Range headwaters of Percha Creek. Clasts are poorly to moderately sorted, subangular to rounded, and consist of pebbles (50-70%), cobbles (20-30%), and boulders (10-20%) up to 2.5 m (8.2 ft) across. Matrix consists of dark grayish brown to grayish brown (10YR 4-5/2) or very pale brown (10YR 8/2), poorly to very well sorted, subangular to rounded, clayey silt to coarse-grained sand. Fine-grained (silty clay) channel margin deposits may be very dark grayish brown (10YR 3/2). Deposit preserves bar-and-swale topography with up to 1 m (3.3 ft) of relief. Total thickness is unknown but likely 1-3 m (3.3-9.8 ft).

Qamh Modern and historic alluvium, undivided (present to ~800 years old) – Modern alluvium (**Qam**) and subordinate historic alluvium (**Qah**). See detailed descriptions of each individual unit.

Qah Historic alluvium (~50 to ~800 years old) – Sandy pebble to pebble-cobble gravel found in valley bottoms. Deposit is unconsolidated, matrix- to clast-supported, and massive to horizontally laminated in medium, tabular beds with subordinate lenticular channel lags composed of pebbles and cobbles. Clasts include moderately well sorted, subangular to subrounded pebbles (90%) and cobbles (10%) of Tertiary volcanic lithologies with rare Santa Fe Group conglomerate (5-10%). Matrix consists of brown to grayish brown (10YR 4/3 to 5/2), well sorted, subrounded, silty, very fine- to fine-grained sand with 40% feldspar, 30% lithic, and 30% quartz grains. Deposit may preserve moderate bar-and-swale topography with up to 30 cm (12 in) of relief. Tread height 0.6-1.2 m (2-3.9 ft) above modern grade. Base not observed in thickest deposits; perhaps up to 2.5 m (8.2 ft) maximum thickness.

Qahm Historic and modern alluvium, undivided (present to ~800 years old) – Historic alluvium (**Qah**) and subordinate modern alluvium (**Qam**). See detailed descriptions of each individual unit.

Qahy Historic and younger alluvium, undivided (~50 to middle Holocene) – Historic alluvium (**Qah**) and subordinate younger alluvium (**Qay**). See detailed descriptions of each individual unit.

Qary Recent and younger alluvium, undivided (present to middle Holocene) – Historic and modern alluvium (**Qah** and **Qam** as undivided "recent" deposit *Qar*) and subordinate younger alluvium (**Qay**). See detailed descriptions of these individual units. Generally ≤ 5 m (16.4 ft) thick.

Qay Younger alluvium, undivided (middle to upper Holocene) – Cobbly sand underlying low-lying terraces in valley bottoms. Deposit is unconsolidated, mostly matrix-supported, massive to cross-stratified in thin to thick, tabular to lenticular beds. Clasts consist of moderately well sorted, subrounded to rounded pebbles (40%) and cobbles (60%), and are occasionally imbricated in small lenses. Clast lithologies are generally 75-80% Tertiary volcanic and 25-30% Paleozoic sedimentary rocks; stream systems draining Paleozoic outcrops in the eastern part of the quad have higher percentages of Paleozoic clasts. Matrix consists of brown (10YR 5/3), moderately well sorted, subrounded to rounded, silty, very fine- to medium-grained sand comprised of 40% feldspar, 40% quartz, and 20% lithic grains. Deposit exhibits little to no pedogenic carbonate development. Surface preserves subdued bar-and-swale topography with 10-20 cm (4-8 in) of local relief. Tread height 1.6-1.8 m (5.2-5.9 ft) above modern grade. Base of thickest deposits not observed; perhaps up to 3 m (9.8 ft) maximum thickness.

Qaym Younger and modern alluvium, undivided (present to middle Holocene) – Younger alluvium (**Qay**) and subordinate modern alluvium (**Qam**). See detailed descriptions of each individual unit.

Qayh Younger and historic alluvium, undivided (~50 years old to middle Holocene) – Younger alluvium (**Qay**) and subordinate historic alluvium (**Qah**). See detailed descriptions of each individual unit.

Qayr Younger and recent alluvium, undivided (present to middle Holocene) – Younger alluvium (**Qay**) and subordinate historic and modern alluvium (**Qah** and **Qam** as undivided –recent” deposit *Qar*). See detailed descriptions of these individual units. **Qayr** found in eastern part of quad consists of sandy gravel filling low-relief basins incised into **Tsf** and **QTp**. Deposit is unconsolidated, mostly matrix-supported, massive to weakly imbricated, and normally graded in medium to thick, tabular to lenticular beds. Clasts consist of poorly sorted, subangular to subrounded pebbles (55%), cobbles (40%), and boulders (5%). Clast lithologies include 45-50% andesite/breccia of Copper Flat, 45-50% Black Range volcanics, and ≤ 5% Paleozoic carbonate lithologies. Matrix consists of light yellowish brown (10YR 6/4), poorly to moderately sorted, subangular to subrounded, silty, very fine- to medium-grained sand comprised of 60% lithic, 35-40% feldspar, and ± 5% quartz grains, as well as ≤ 5% clay films. Deposit is carbonate-cemented in lower 1.7 m (5.6 ft). Generally 4-7 m (13-23 ft) thick.

Ql Lacustrine sediment (middle to upper Holocene) – Fine-grained sediment filling valley of Trujillo Creek. Deposit is unconsolidated, dominantly matrix-supported, and massive to horizontally laminated in very thin to medium beds that apparently lack varves. Sandier beds may display weak ripple lamination and rare gravel beds are imbricated. The latter consist of thin- to medium-bedded, poorly to moderately sorted, subangular to subrounded pebbles (90-95%) and cobbles (5-10%) of Tertiary volcanic and sedimentary lithologies. These pebble lags are continuous over ~50 m (164 ft). Very rare clay films on clasts. Matrix consists of gray (10YR 5-6/1; 10YR 3/1 wet) clayey silt to fine-grained sand. Deposit is strongly calcareous but rarely exhibits stage I carbonate morphology. Bioturbated throughout (coarse roots). 6.1-9 m (20-29.5 ft) thick.

Quaternary stream terrace deposits

Unless otherwise noted, gravel is composed of subrounded to rounded plagioclase-phyric andesite (45-65%), Kneeling Nun Tuff (5-20%), and up to 20% Paleozoic carbonate clasts.

Stream terrace deposits of Percha Creek and its tributaries

Qao Stream terrace deposit, undivided (middle to upper Pleistocene) – Sandy gravel occurring in strath terrace deposits 1.7-4.1 m (5.6-13.5 ft) thick with surfaces higher than those associated with **Qay**. Clast compositions are dominated by Tertiary volcanic lithologies derived from the eastern face of the Black Range, but may include subordinate Paleozoic carbonates, particularly downstream of Percha Box. This unit is locally subdivided into 3-5 terraces whose heights differ in elevation above modern stream grade:

Qao_3 Third or youngest terrace deposit (upper Pleistocene) – Sandy pebble-cobble gravel in medium to thick, lenticular beds. Deposit is unconsolidated, clast-supported, and imbricated. Clasts consist of poorly sorted pebbles (55%), cobbles (40-45%) and subordinate boulders (0-5%). Approximately 50-60% of clasts at the surface of the deposit are varnished. Matrix consists of brown to light brown (7.5YR 4-6/4), poorly to moderately sorted, subangular to subrounded, silty, very fine- to coarse-grained sand comprised of 50% feldspar, 30% quartz, and 20% lithic grains. Little to no pedogenic carbonate development. Tread is 6.2-8.5 m (20.3-27.9 ft) above modern grade, but locally may be slightly lower (~5 m above grade) in which case deposit is mapped as **Qao_{3b}**. 1.7-3.8 m (5.6-12.5 ft) thick downstream of Percha Box.

Qao_2 Second terrace deposit (middle Pleistocene?) – Similar to **Qao_1** deposit with variable varnish on clasts at surface and up to 50% of clasts coated by carbonate (stage I+ carbonate morphology). Clast lithologies include up to 15-20% Paleozoic sedimentary facies and 15-20% Precambrian granite. Generally subordinate to **Qao_1** and **Qao_3** terrace deposits. Tread is 13.6-13.8 m (44.6-45. 3 ft) above modern grade, but locally may be slightly higher (~15-16 m above grade) in which case deposit is mapped as **Qao_{2a}**. 1.7-2.0 m (5.6-6.6 ft) thick downstream of Percha Box.

Qao_1 First terrace deposit (middle Pleistocene?) – Sandy pebble-cobble-boulder gravel in thick, lenticular beds. Deposit is unconsolidated, clast-supported, and imbricated. Clasts consist of poorly to moderately sorted pebbles (40%), cobbles (55%) and boulders (5%). Up to 70% of clasts at the surface are varnished. Clast lithologies are dominated by Tertiary andesite (60-70%) with subordinate Kneeling Nun Tuff (20%). Matrix consists of brown to grayish brown (10YR 4/3 to 5/2), moderately sorted, subangular to subrounded, silty, very fine- to medium-grained sand comprised of 45% feldspar, 40% quartz, and 15% lithic grains. Upper fine-grained overbank deposits may be variably deflated, and are commonly brown (7.5YR 4/3) where mixed with eolian material. Approximately 30-70% of clast undersides are carbonate-coated (stage I+ carbonate morphology). Tread is 20.8-21.5 m (68-70.5 ft) above modern grade. 2.1-4.1 m (6.9-13.5 ft) thick downstream of Percha Box.

Qao_0 **Oldest terrace deposit (middle Pleistocene?)** – Collection of loose, subrounded to rounded cobbles and boulders of Paleozoic limestone and sandstone, and Tertiary volcanic clasts on the south side of Percha Box. Tread is 36-38 m (118-125 ft) above modern grade. 1-2 m (3.3-6.6 ft) thick.

Quaternary alluvial fan units

Fan gravel is dominated by the lithologies exposed in the catchments from which fans emanate. Clasts are typically angular to subangular, unless otherwise noted.

Qafmh **Modern and historic fan alluvium, undivided (0 to ~800 years old)** – Pebbly sand to sandy pebble-cobble gravel in medium to thick, tabular beds. Unconsolidated, matrix-supported, and massive. Maximum thickness ~3 m (9.8 ft).

Qafhm **Historic and modern fan alluvium, undivided (0 to ~800 years old)** – Historic fan alluvium (**Qafh**) and subordinate modern fan alluvium (*Qafm*). See detailed descriptions of **Qafmh** and **Qafh**.

Qafh **Historic fan alluvium (~50 to ~800 years old)** – Sandy gravel in medium to thick, tabular beds graded to the surface of **Qah**. Deposit is unconsolidated, clast- to matrix-supported, and massive. Clasts consist of poorly sorted, angular to subrounded pebbles (50-55%), cobbles (40%), and boulders (5-10%) and may be weakly imbricated in the lower 30-40 cm (12-16 in) of the deposit. Matrix consists of very dark grayish brown (10YR 3/2), poorly sorted, subangular to subrounded, silt to medium-grained sand comprised of 60% quartz, 30% feldspar, and 10% lithic grains. Little or no soil development or varnishing of clasts at surface. 0.8-1.2 m (2.6-3.9 ft) thick.

Qafy **Younger fan alluvium (middle to upper Holocene)** – Sandy gravel in thick to very thick, tabular to lenticular beds graded to the surface of **Qay**. Deposit is unconsolidated, matrix-supported, and massive. Clasts consist of poorly sorted pebbles (85%), cobbles (10%), and boulders (5%). Matrix consists of dark grayish brown (10YR 4/2), poorly to moderately sorted, subangular to subrounded, silty, very fine- to medium-grained sand with subequal amounts of feldspar and lithic grains. In Warm Springs Canyon, deposit may be capped by 0.9-1 m (3-3.3 ft) soil profiles with 50 cm (20 in) Bt horizons featuring clay films on clasts; may also include Btk horizons with stage I+ carbonate morphology. 2.2-3 m (7.2-9.8 ft) thick.

Qafyh **Younger and historic fan alluvium, undivided (~50 years old to middle Holocene)** – Younger fan alluvium (**Qafy**) and subordinate historic fan alluvium (**Qafh**). See detailed descriptions of each individual unit.

Qafyr Younger and recent fan alluvium, undivided (0 years old to middle Holocene) – Younger fan alluvium (**Qafy**) and subordinate –recent" fan alluvium *Qafr* (**Qafmh**, **Qafhm**, and **Qafh**, undivided). See detailed descriptions of each individual unit.

Older alluvial fan deposits graded to stream terraces of Percha Creek and its tributaries

Qafo Older alluvial fan deposits, undivided (middle to upper Pleistocene) – Sandy gravel occurring in fan deposits 1.7-4 m (5.6-13.1 ft) thick graded to surfaces associated with **Qao_1**, **Qao_2**, and **Qao_3**. Near Copper Flat, up to 85% of clasts consist of Cretaceous andesite and/or breccia. This unit is locally subdivided into three deposits:

Qaf_3 Alluvial fans graded to the level of Qao_3 stream terraces (upper Pleistocene) – Sandy pebble or pebble-cobble-boulder gravel in thin to medium, lenticular beds. Deposit is unconsolidated, clast- to matrix-supported, and massive to weakly imbricated. Clasts consist of very poorly to moderately sorted, subangular to subrounded pebbles (50-70%), cobbles (30-40%), and boulders (10-20%) up to 1.4 m (4.6 ft) across. Matrix consists of light brown (7.5YR 6/4), moderately sorted, angular to subrounded, fine- to coarse-grained sand with approximately 50% feldspar, 40% quartz, and 10% lithic grains. Deposit is commonly overlain by modest soil profiles up to 60 cm (24 in) thick with lower Bk horizons exhibiting stage I+ to II carbonate morphology. 1.7-2.3 m (5.6-7.5 ft) thick.

Qaf_2 Alluvial fans graded to the level of Qao_2 stream terraces (middle Pleistocene?) – Sandy pebble gravel and occasional, discontinuous lags of cobble-boulder gravel in medium to very thick, tabular beds. Deposit is unconsolidated, dominantly matrix-supported and massive with rare, imbricated gravel. Clasts consist of very poorly to poorly sorted pebbles (85%), cobbles (10%), and boulders (5%). Clasts are moderately well varnished at the surface. Matrix consists of brown (7.5YR 4/4) to strong brown (7.5YR 5/6), poorly sorted, subangular, fine- to coarse-grained sand with subequal amounts of feldspar and lithic grains. Calcic horizons or soil carbonate development is uncommon. Fans form planar erosional surfaces on Santa Fe Group gravels in many valley bottoms. Typically ~4 m (13.1 ft) thick.

Qaf_1 Alluvial fans graded to the level of Qao_1 stream terraces (middle Pleistocene?) – Sandy gravel in tabular beds. Deposit is unconsolidated, clast- to matrix-supported and massive. Clasts consist of poorly sorted, angular to subrounded pebbles (65-90%), cobbles (20-30%), and boulders (5-10%). Clasts are heavily varnished at the surface. Matrix consists of dark yellowish brown (10YR 3-4/4), poorly to moderately sorted, subangular to subrounded, silty, very fine- to coarse-grained sand comprised of 65-70% lithic and 30-35% feldspar grains. Deposit is generally poorly preserved due to erosion; maximum thickness no more than ~3.5 m (11.5 ft).

Quaternary piedmont deposits

Qapy Younger piedmont alluvium (middle to upper Holocene) – Pebbly sand in very thick, tabular beds. Deposit is unconsolidated, matrix-supported, and massive. Clasts consist of poorly to moderately sorted, angular to subangular pebbles and, infrequently, veneers of non- to very weakly varnished pebble-cobble gravel. Matrix consists of dark yellowish brown (10YR 4/4), well sorted, sandy silt. Stage I carbonate morphology may be observed in upper 20 cm (8 in). 1.7-2 m (5.6-6.6 ft) thick

Qapo Older piedmont alluvium (middle to upper Pleistocene) – Sandy gravel in medium to thick, tabular to lenticular beds. Deposit is unconsolidated, clast- to matrix-supported, and massive to weakly imbricated. Gravel occurs in lenticular pebble-cobble stringers or imbricated pebble-cobble-boulder beds. Clasts consist of very poorly sorted, angular to subrounded pebbles (75%), cobbles (20-25%), and boulders (0-5%). Clasts are moderately to strongly varnished at the surface. Matrix consists of light brown (7.5YR 6/4), moderately sorted, subangular to subrounded, fine- to coarse-grained sand comprised of 10-60% quartz, 10-40% feldspar, and 20-70% lithic grains. Stage II-III carbonate morphology (masses, nodules) may be observed. 2.2-3.8 m (7.2-12.5 ft) thick.

Quaternary hillslope and landslide deposits

Qca Colluvium and alluvium, undivided (middle Pleistocene and Holocene) – Poorly sorted silt to boulders transported by gravity and alluvial processes, forming aprons around highlands. Highly variable thickness; probably no more than 5-8 m (16.4-26.2 ft).

Qls Landslide deposits, undivided (middle to upper Pleistocene?) – Non-stratified, cobble-boulder gravel. Deposit is unconsolidated, clast- to matrix-supported, and massive with vague reverse grading. Clasts consist of very poorly sorted, angular to subangular cobbles and boulders with subordinate gravels. Larger clasts may be oriented with their long axes parallel to slope. Matrix consists of dark brown (10YR 3/3), poorly sorted, subangular to subrounded, silty, very fine- to coarse-grained sand. Underlies steep escarpments of Copper Flat andesite/breccia or **Tb.** Maximum thickness may be up to 10 m (33 ft). West of Percha Creek narrows, two large landslide deposits are mapped individually:

Qls_2 Younger Percha Creek narrows landslide deposit (middle Pleistocene?) – Poorly stratified, bouldery gravel. Deposit is mostly unconsolidated, clast- to matrix-supported, massive, and occasionally reverse graded. Clasts consist of very poorly sorted, angular to subangular pebbles (10-20%), cobbles (40-60%), and boulders (30-40%) up to 3 m (9.8 ft) in diameter that are rarely carbonate-coated. Clasts are often oriented with long axes parallel to slope. Matrix consists of dark brown (10YR 3/3) to pinkish gray (7.5YR 7/2), very poorly to poorly sorted, angular to subrounded, silty clay to silty, very fine- to very coarse-grained sand comprised of $\geq$ 90% lithic grains. Elsewhere, deposit is supported by sand, pebbles, and small cobbles weathered from basaltic andesite; these weathered clasts support larger, subrounded boulders. Deposit features blocks of andesite 10s of meters across with chaotic fracturing, Thickness unknown.

Qls_1 Older Percha Creek narrows landslide deposit (middle Pleistocene?) – Poorly stratified, bouldery gravel similar to **Qls_2** but occupying a lower position in the landscape. Deposit contains boulders up to 3 m (9.8 ft) long on gentle (commonly 2-3°) slopes up to 1 km (0.62 mi) or more away from steep escarpments formed by source exposures of **Tb** and **Ta**. Hummocky landscape underlain by the deposit features distinct run-out toes and occasional lobes of open-framework cobbles (60%) and boulders (40%) of **Tb**. Matrix consists of very dark grayish brown (2.5Y 3/2), poorly to moderately sorted, subangular to subrounded, clayey silt and very fine- to medium-grained sand. Thickness unknown.

Quaternary-Tertiary basin-fill

QTp Palomas Formation of the Santa Fe Group (lower Pliocene to middle Pleistocene) – Sandy gravel and conglomerate in medium to very thick, tabular beds capping erosional surfaces on **Tsf** in the east-central part of the quad. Deposit is unconsolidated to moderately carbonate-cemented, mostly clast-supported, and massive to imbricated. Pebble gravel/conglomerate and pebbly sand/sandstone beds make up 5-15% of the deposit; the former are commonly planar cross-stratified. Clasts consist of very poorly to poorly sorted, subangular to subrounded pebbles (45-50%), cobbles (40-45%), and boulders (5-15%) of up to 50% Tertiary Black Range-derived andesitic lithologies, ~25% Cretaceous andesite of Copper Flat, and ~15% Pliocene basalt. Imbricated clasts trend ESE (105°). Matrix consists of pinkish white (7.5YR 8/2) to very pale brown (10YR 7/4), poorly to moderately well sorted, angular to subrounded, silt to coarse-grained sand comprised of 50-80% lithic, 15-50% feldspar, and ≤ 5% quartz grains. Unit forms gentle to moderate slopes and ledges. Maximum thickness 5-15 m (16-49 ft).

QTpl Palomas Formation limestone (lower Pliocene to middle Pleistocene) – Tan to gray weathering gray, fine to medium crystalline limestone with 5-10% vugs filled with sparry calcite. Medium-bedded limestone is nearly horizontal. A few unidentifiable bivalve shells are preserved near the top of the exposure. 3-5 m (9.8-16.4 ft) thick.

Tsf Santa Fe Group predating the Palomas Formation (Miocene-Pliocene) – Pebbly sand/sandstone, pebble-granule gravel/conglomerate, and pebble-cobble gravel/conglomerate in thin to thick, tabular beds. Subordinate beds include pebble-cobble-boulder gravel/conglomerate in thin to thick, tabular to broadly lenticular beds and channel lags. Unit is unconsolidated to moderately silica-cemented or, rarely, carbonate-cemented. Beds are typically matrix-supported and massive to weakly planar or trough cross-bedded with foresets up to 25 cm (10 in) high. Horizontal laminations may occur in finer-grained facies. Cross-stratification is more common in pebbly sand or pebble-granule beds, whereas imbrication is observed in pebble-cobble and pebble-cobble-boulder gravel/conglomerate. Clasts consist of very poorly to moderately sorted, angular to subrounded pebbles (55-95%), cobbles (10-40%), and boulders (0-15%). Boulders may be up to 0.75 m (2.5 ft) across. Clast lithologies vary but may include ≤ 80% sanidine-rich rhyolite, ≤ 50% Cretaceous andesite of Copper Flat, and ≤ 22% Kneeling Nun Tuff. Paleozoic carbonate clasts are rare (≤ 5%). Matrix consists of poorly to moderately well sorted, angular to subrounded, silty, very fine- to coarse-grained sand or, rarely, clayey silt. Sandy matrix is comprised of 10-70% lithic, 5-70% quartz, and 20-40% feldspar grains, and occasionally up to 5% clay films. Matrix color varies greatly, from light reddish brown to pink (2.5YR 7-8/3) to light yellowish brown (10YR 6/4); pale brown (10YR 6/3) is perhaps most common. Differences in hue are due to silica- versus carbonate-cementation, grain lithology, or both, with silica-cemented beds of volcanic litharenite typically redder than carbonate-cemented beds with higher percentages of quartz and/or feldspar grains. Silica entirely replaces the matrix in select outcrops. Unit typically forms moderate to steep, rubbly slopes but cemented beds may form prominent ledges and small cliffs. A very fine-grained white ash with tiny biotite is preserved between two sandy cobble-boulder conglomerate beds at UTM 256502E 3643474N (NAD 83). Maximum thickness 204 m (669 ft).

Tt Thurman Formation (middle to upper Oligocene) – Pebbly to silty sandstone and pebble-cobble conglomerate in thickly laminated to medium, tabular to perhaps lenticular beds. Unit fills in small paleovalley cut into **Td**, **Taqh**, and **Tba_1** in southwestern part of quad, and is weakly consolidated, mostly matrix-supported, and broadly cross-stratified. Pebble lags/lenses are rare. Clasts include moderately well sorted, angular to subrounded pebbles (80-90%) and cobbles (10-20%) of ≤ 55% Kneeling Nun Tuff, ≤ 40% basaltic andesite, and ≤ 5% older andesite. Matrix consists of pale brown (10YR 6/3), well sorted, subrounded to rounded, fine- to medium-grained sand or white (10YR 8/1), well sorted silt to very fine-grained sand. Grains are comprised of 45% feldspar, 35% lithic fragments, and 20% quartz. Silty, very fine-grained sand occurs in laminated beds, typically isolated or occurring in couplets or triplets. Occasional small (≥ 0.5 mm thick) concentrations of iron oxide minerals are found in both pebbly and silty sand beds. Approximately 30 m (98 ft) thick.

Tertiary volcanic and volcaniclastic units

Tb Basalt flows (lower Pliocene) – Dark bluish to very dark gray or black weathering grayish brown to tannish gray, aphanitic to aphanitic-porphyritic, fine- to medium-grained basalt. The weathered surfaces of these flows commonly have a spotted or speckled appearance. Forms ledges and cliffs capping mesas throughout quadrangle. Phenocrysts include 3-7% pyroxene (0.5-1.5 mm, anhedral to subhedral, commonly weathered), 0-5% plagioclase (1-5 mm, anhedral to subhedral), and 1-3% olivine (0.75-2 mm, anhedral to subhedral). One basalt flow in western part of quad may contain up to 17% plagioclase phenocrysts in a glassy groundmass. Dense to somewhat vesicular, with vesicles constituting up to 20% of rock. Commonly contains amygdules filled by silica and/or zeolites. May exhibit weakly to moderately developed columnar jointing. Red cinder deposits at the base of the basalt flow on Black Peak are ~ 1 m (3.3 ft) thick on the south side of the exposure and 10 m (33 ft) thick on the north side. Flows capping a mesa southwest of Warm Springs Canyon consist of: (A) cindery to amygdaloidal, aphanitic basalt in lower 2-3 m (6.5-10 ft); (B) hackly weathering, fine-grained basalt in middle ~12 m (39 ft); and (C) somewhat vesicular to scoriaceous, aphanitic basalt in upper 9.5-10.5 m (31-34.5 ft). The Warm Springs Canyon basalt was dated by Seager et al. (1984) at 4.2 ± 0.1 Ma ($^{40}K/^{40}Ar$). Maximum thickness 40 m (131 ft).

Tvs Volcaniclastic deposits, undivided (Oligocene) – Stratigraphically isolated pockets of volcaniclastic debris flows on Paleozoic rocks south of Copper Flat. One deposit has pebbles and granules of dacite with hornblende and biotite. 1-5 m (3.3-16.4 ft) thick.

Tat Andesite of Trujillo Peak (upper Oligocene?) – Dark gray to purplish brown weathering tannish gray, aphanitic to aphanitic-porphyritic, fine- to medium-grained andesite. Forms steep, rubbly slopes, ledges, and cliffs below Trujillo Peak. Phenocrysts in lower interval include 2-3% pyroxene (2-4 mm, subhedral, commonly altered) and 1-2% hornblende (1-2 mm, euhedral, commonly zoned). Locally subdivided into 2 units:

Tat_2 Upper andesite of Trujillo Peak – Alternately dense and scoriaceous to vesicular. Vesicles contain silica or calcite amygdules. Lacks hornblende phenocrysts. Forms steep, rubbly slopes and ledges. Approximately 80 m (262 ft) thick.

Tat_1 Lower andesite of Trujillo Peak – Non-vesicular and strongly foliated. Forms ledges and cliffs. Approximately 120 m (394 ft) thick.

Td Dacite (upper Oligocene) – Medium to dark gray weathering light reddish to tannish brown, hackly weathering, porphyritic-aphanitic, fine- to coarse-grained dacitic lava flows and block and ash breccia. Forms ledges and steep, rubbly slopes. Phenocrysts include 8% plagioclase (1-5 mm, anhedral to subhedral), 3-4% pyroxene (1-3 mm, anhedral; occasionally overprints plagioclase), trace to 5% quartz (≤ 2 mm, anhedral), trace biotite (≤ 2 mm, subhedral to euhedral), and trace hornblende (≤ 2 mm, subhedral to euhedral). Flows to in the northwestern part of the quad contain 10% total phenocrysts of 3-4 mm feldspar, hornblende, biotite, and quartz. Gray matrix. Flows are non-vesicular and foliated, with 1.5-8 cm (0.6-3.1 in) thick flow-layering. Minor epidote propylitization in places. Coarser grained and less foliated in upper 15 m (49 ft). Breccia is composed of monolithologic clasts with 10-15% total phenocrysts of 5-6 mm sanidine, biotite, hornblende, quartz, and zoned potassium feldspar. The center of the latter crystals is replaced by quartz. Maximum thickness is 35 m (115 ft).

Tttc Tuffaceous volcaniclastic sediment of Tank Canyon (upper Oligocene) – Laminated, tabular beds of weakly sorted volcaniclastic conglomerate with minor volumes of laminated, fine-grained ash beds < 10 cm (4 in) thick, ignimbrites < 1 m (3.3 ft) thick, and fluvial conglomerate and sandstone < 3 m (9.8 ft) thick. Bedding in the laminated unit is decimeter- to meter-scale and is normally graded. The < 50 cm (20 in) clasts in the graded conglomeratic intervals are angular and are of mixed volcanic rock types that include flow-banded rhyolite with quartz and sanidine, white fine-grained rhyolite, equigranular felsic intrusive rocks, and porphyritic basaltic andesite; volcanic clasts make up to 50% of each bed. Aphyric pumice that is < 1 cm (0.4 in) across makes up 10-40% of the unit. Matrix is ashy to sandy. Laminated hyperconcentrated deposits are interbedded with conglomerates and sandstone with fluvial cross-bedding and scoured channels. 30 to 60 m (98-197 ft) thick.

Tr Rhyolite (upper Oligocene) – Porphyritic rhyolite flows that are variably massive to flow banded. In the thicker parts of the section, the flows are more crystal rich (15-25%) and pink at the top, and more crystal poor (3-10%) and gray near the base. Block and ash deposits near the base are common. Phenocrysts include sanidine, quartz, biotite, and hornblende. Two meters of tephra at the base of the unit is preserved at UTM 255020E 3646679N (NAD83); the laminated part of deposit is composed of granules of rock fragments and a few grains of biotite in an ashy matrix that is normally graded. Pumice in the tephra is aphyric and altered. Rock fragments in the laminated deposit have phenocrysts of biotite and sanidine; quartz is not obvious. The rhyolite flow unit is intercalated with **Tba_2** and may correlate with *Tr4* of Seager et al. (1982). This unit was included in *T4ba* by (Seager et al., 1982). The rhyolite flow unit is variable in thickness, ranging from 15 to 120 m (49-394 ft); thins toward the south.

Tba_2 Younger basaltic andesite (upper Oligocene) – Mafic flows with a black to dark gray aphyric to crystalline matrix and 1-2% phenocrysts of plagioclase laths, subrounded olivine, and pyroxene < 3-4 mm across. Flows are commonly strongly foliated in the core and vesicular at the top. North of the Percha Narrows, this unit correlates to *T4ba* of Seager et al. (1982). Up to 300 m (984 ft) thick.

Tbi Basaltic andesite dike (upper Oligocene) – Mafic dike with a black to dark gray aphyric matrix and 1-2% phenocrysts of plagioclase, olivine, and pyroxene < 3-4 mm across that appears to be the feeder for one of the younger basaltic andesite flows.

Tbah Hydromagmatic deposits in younger basaltic andesite (upper Oligocene) – Gray, sandy hydromagmatic deposit with tabular, laminated, weakly graded bedding with white to pink altered clasts that make up 2-3% of the rock; fragmented basalt pieces with << 1% olivine are generally < 4 mm across. 1 m (3.3 ft) thick

Ta Aphanitic trachyandesite (upper Oligocene) – Massive to variably foliated, vesicular, aphanitic to aphanitic-porphyritic, fine-grained trachyandesite. Phenocrysts include < 3% total plagioclase, biotite, hornblende, and pyroxene. May contain small quartz xenocrysts. Matrix is brown to light gray and trachytic. Commonly altered to yellowish color. Vesicles often contain acicular zeolites. May be fractured, featuring apparent columnar jointing. Approximately 98 m (320 ft) thick.

Tavs Volcaniclastic debris flows with quartz-hornblende andesite/dacite clasts (upper Oligocene) – Well indurated, heterolithic volcaniclastic debris flow deposit containing blocks up to 0.5 m (1.6 ft) in diameter. Blocks are poorly sorted, angular, and are found in a pink, sandy matrix. Other intervals may consist of fine-grained sandstone containing 3-5% granules of volcanic rocks, including **Taqh**. Maximum thickness approximately 27 m (90 ft).

Taqh Quartz-hornblende andesitic to dacitic flows and flow breccias (upper Oligocene) – Aphanitic to porphyritic andesite to dacite flows and flow breccias. Phenocrysts include 1-2% total quartz (3 mm), pyroxene (< 2 mm), plagioclase, and altered hornblende. May contain disseminated magnetite. Breccia is clast- to matrix-supported and contains angular blocks up to 0.5 m (1.6 ft) in diameter. At least 50 m (164 ft) thick.

Tba_1 Older basaltic andesite (lower to upper Oligocene?) – Medium bluish or purplish gray to dark gray weathering grayish tan to dark reddish brown, porphyritic-aphanitic to porphyritic, fine- to coarse-grained andesite. Forms ledges and small cliffs throughout western part of quadrangle. Phenocrysts include 2-10% pyroxene (≤ 2 mm, anhedral to subhedral), 3-8% plagioclase (0.5-4 mm, anhedral to subhedral), ≤ 5% olivine (≤ 1 mm, anhedral), and trace to 6% hornblende (≤ 6 mm, subhedral to euhedral). Dense to vesicular, with vesicles filled by chalcedony or drusy quartz. Strongly foliated in middle intervals exposed along Percha Creek narrows in western part of quad; occasionally flow-banded in aphanitic intervals. Contains rare amygdules up to 1 cm (0.4 in) filled by silica, zeolites, and/or goethite. Correlates to units *Tpl* of Hedlund (1977) and *T4ba* of Seager et al. (1982). A sample from Percha Creek narrows was dated by Seager et al. (1984) at 28.1 ± 0.6 Ma (^{40}K/^{40}Ar). Approximately 470 m (1534 ft) thick.

Tba_1vs Volcaniclastic debris flows interbedded with basaltic andesite (lower to upper Oligocene?) – Maroon brown volcaniclastic conglomerate in poorly stratified, medium to very thick beds. Massive to weakly imbricated. Clasts include very poorly sorted, mostly subangular pebbles, cobbles, and boulders of aphanitic to porphyritic-aphanitic, plagioclase-phyric andesite. Finer-grained intervals may display flow-banding. Matrix contains 5-10% plagioclase, 5% hornblende, and 2% quartz phenocrysts. Forms ledges and very steep, rubbly slopes south of Percha Creek. Maximum thickness 102 m (335 ft).

Tss Lacustrine sediment (lower to upper Oligocene?) – Silty sandstone and sandy siltstone in thick laminae and thin beds. Unit is very weakly silica-cemented and horizontally laminated to planar or trough cross-bedded. Sandstone matrix consists of light yellowish brown (2.5Y 6/4) to pale brown (2.5Y 7/3), moderately to well sorted, subangular to subrounded, slightly silty, very fine- to medium-grained sandstone comprised of 50% quartz, 40% feldspar, and 10% lithic grains. Siltstone contains dark brown laminations of clayey silt occurring at 2-10 mm intervals. Weathers into chips containing coarse, angular biotite grains. Both bed types commonly contain limonite concretions and lenses up to 8 cm (3.1 in) wide. North of the Percha Creek narrows, this unit is more conglomeratic and has fluvial cross-beds. The cross-bedded, conglomeratic, pebbly to bouldery sandstone has rounded clasts < 1-40 cm (0.4-16 in) in diameter composed of fine-grained lava and rhyolite and sand that includes quartz and volcanic grains. Maximum thickness 37 m (121 ft).

Tcb Caballo Blanco Rhyolite Tuff (lower Oligocene) – Cross-section only. White to light gray, crystal-rich ash-flow tuff. Phenocrysts include sanidine, oligoclase, and quartz that constitute 25-35% of rock (Seager, 1986). ^{40}Ar/^{39}Ar dated at 32.06 ± 0.12 Ma (scaled upward by 1.3% from McIntosh et al. [1991] based on 28.02 Ma Fish Canyon Tuff calibration age). Maximum thickness approximately 91 m (300 ft).

Tmr Mimbres Peak Formation rhyolite (upper Eocene) – Light purplish gray, dense, strongly flow-banded, aphanitic rhyolite. Laterally (?) grades into very light gray weathering light tan, flow-banded, porphyritic-aphanitic, brecciated block and ash-flow tuff west of Percha Creek narrows. Phenocrysts there include up to 5% sanidine (1-2.5 mm, euhedral). May contain spherulites. $^{40}Ar/^{39}Ar$ dated at 34.32 ± 0.11 to 34.22 ± 0.16 Ma (O'Neill et al., 2002). Maximum thickness 52 m (171 ft).

Tkn Kneeling Nun Tuff (upper Eocene) – Gray to dark maroon-brown, porphyritic, moderately to densely welded ash-flow tuff. Forms ledges or bold cliffs throughout quadrangle. Phenocrysts include 6-24% quartz (1-4 mm, anhedral), trace to 6% biotite (0.5-1.5 mm, euhedral, rarely zoned), trace to 4% hornblende (≤ 1.5 mm, subhedral to euhedral), and trace to 2% plagioclase (≤ 1.75 mm, subhedral, occasionally zoned). Total phenocryst content increases up-section. Non- to slightly vesicular, with moderately to strongly flattened pumice in welded sections (length:width ratios of 3:1 to 10:1). Flattened lithic fragments and/or pumice typically have length:width ratios of 6:1 to 8:1. Lower intervals contain spherulites 1-4 cm (0.4-1.6 in) in diameter. $^{40}Ar/^{39}Ar$ dated at 35.34 ± 0.10 Ma (scaled upward by 1.3% from McIntosh et al. [1991] based on 28.02 Ma Fish Canyon Tuff calibration age). 7-156 m (23-512 ft) thick.

Ts Sugarlump Tuff (upper Eocene) – Pinkish to tannish white, non- to somewhat welded, porphyritic-aphanitic to porphyritic, fine- to coarse-grained, lithic-rich ash-flow tuff. Forms moderate to steep slopes and occasional ledges. Phenocrysts include 3-15% quartz (1-3 mm, anhedral to subhedral), trace-9% biotite (≤ 1 mm, euhedral), and 0-6% hornblende (1-2 mm, subhedral). Lithic fragments (typically flow-banded rhyolite) make up to 35% of visible grains and occur as coarse ash to lapilli. Occasional blocks of lithic fragments up to 25 cm (10 in) were observed in the upper 6 m (20 ft) of unit in Trujillo Park Canyon. Pinkish tan pumice fragments up to 3 cm (1.2 in) are common (≤ 70%). Densely welded in upper 1.5-12 m (4.9-39 ft); non-welded elsewhere. In middle and upper intervals, tuff may be interbedded with tannish gray, very thin- to thin-bedded, weakly cross-bedded, somewhat poorly sorted, subangular to subrounded, medium- to coarse-grained sandstone. Less commonly, middle intervals may include interbedded, greenish gray to brownish green, matrix-supported, moderately well sorted, subrounded, small (0.5-1 cm) pebble gravel. Clastic grains are up to 70% quartz. $^{40}Ar/^{39}Ar$ dated at 35.63 ± 0.15 Ma (scaled upward by 1.3% from McIntosh et al. [1991] based on 28.02 Ma Fish Canyon Tuff calibration age). Maximum thickness 35 m (115 ft) in Trujillo Park Canyon.

Tbao Older basaltic andesite (upper Eocene?) – Dark gray weathering grayish tan, foliated to dense, porphyritic-aphanitic, fine-grained basaltic andesite. Forms slopes and occasional ledges. Phenocrysts include 4-6% plagioclase (0.5-2 mm, anhedral to subhedral) and 2-4% pyroxene (≤ 1 mm, anhedral). Perhaps correlative to andesite flows interbedded in **Trp**. Maximum thickness approximately 37 m (120 ft).

Trp **Rubio Peak Formation (middle to upper Eocene)** – Whitish to medium dark gray to greenish, thin- to thick-bedded, typically massive, poorly to moderately sorted, silty, very fine- to coarse-grained volcaniclastic sandstone with occasional ~20 cm (8 in) lenses of matrix-supported, subangular pebble or subrounded cobble conglomerate. Uppermost 30 cm (12 in) is horizontally laminated siltstone. Clasts consist of ≥ 85% flow-banded rhyolite in places. Matrix consists of mostly lithic fragments (≥ 75%) with subordinate biotite phenocrysts (≤ 0.75 mm, subhedral). Maximum thickness 55 m (180 ft) in northern Trujillo Park Canyon. Locally subdivided into 2 interbedded units:

Trpl **Andesite flows of the Rubio Peak Formation** – Medium gray, dense, flow-layered andesite with 10% plagioclase, 4-5% hornblende, and trace biotite phenocrysts. This formation includes andesitic lava flows southeast of Percha Creek Box. The altered, massive, light gray lava contains < 2% plagioclase (3-4 mm) and 4-5% total phenocrysts; mafic minerals are altered to clay.

Ꝑme **Exotic block of Magdalena Group limestone** – Observed in Trujillo Park Canyon. Transported during major landslide event(s). See **Ꝑm** description.

Cretaceous volcanic and intrusive units

Ki **Intrusive rocks of Copper Flat, undivided (upper Cretaceous)** – Greenish gray to dull grayish green weathering light tan to dark orange brown, aphanitic-porphyritic to porphyritic, fine- to slightly coarse-grained dikes and plugs intruding andesitic flows and flow breccia of Copper Flat as well as Paleozoic carbonate units north and south of Copper Flat. Phenocrysts include 5-12% plagioclase (≤ 7 mm, anhedral to subhedral laths), trace to 6% hornblende (1-5 mm, subhedral to euhedral), 1-5% pyroxene (1-2 mm, anhedral to subhedral), and trace biotite (1-3 mm, subhedral to euhedral). May contain accessory pyrite up to 0.75 mm. Dikes are commonly 4-8 m (13-26 ft) wide, but may be up to 38 m (125 ft) wide (McLemore et al., 1999). Subdivided into 5 intrusive facies:

Kir **Rhyolitic intrusive rocks** – Pink to white dikes and plugs with 5% phenocrysts of quartz, sanidine, biotite, and hornblende < 4 mm across in an aphanitic to medium-grained, equigranular matrix. Mapped as *Tql* (Tertiary quartz latite) by Hedlund (1977).

Kib **Biotite-phyric intrusive rocks –** White to pink to yellowish white dikes with 5% phenocrysts of potassium feldspar, hornblende, and biotite ± pyroxene that are 3 mm across in a fine- to medium- grained, equigranular matrix.

Kif **Feldspar-phyric intrusive rocks** – Green gray weathering pistachio green, poorly outcropping, and aphanitic-porphyritic. Phenocrysts include 3-5% sanidine (≤ 5 mm, subhedral) and trace quartz (≤ 2 mm, anhedral); may feature a plagioclase-rich groundmass. South of Copper Flat, **Kif** plugs contain 5% feldspar phenocrysts (≤ 4 mm) in a black, equigranular, fine-grained matrix with clots of pyroxene up to 10 mm across. Correlates to unit *Kql* of Hedlund (1977).

Kig **Gabbroic intrusive rocks** – Dark gray to black plug with dark gray plagioclase and pyroxene forming a fine- to medium-grained, equigranular matrix.

Kim **Monzonitic intrusive rocks** – Equigranular plug with a gneissic fabric near its margin. Contains xenoliths of gabbro near its margin. Medium-grained, equigranular matrix is composed of plagioclase, potassium feldspar, and biotite; quartz is not present. Chilled margin is porphyritic with potassium feldspar phenocrysts 5-7 mm long and altered biotite.

Kit **Intrusive rocks of Trujillo Creek (upper Cretaceous)** – Dark bluish gray weathering orange tan, porphyritic, fine- to medium-grained andesite. Forms rubbly knobs and small ledges along Trujillo Creek and its tributaries west and northwest of Trujillo Peak. Phenocrysts include 8-10% plagioclase (0.5-3 mm, anhedral), 5-6% hornblende (1-5 mm, euhedral laths), and 2-4% pyroxene (0.5-4 mm, anhedral). Hornblende and pyroxene show graphic texture with plagioclase in places. Slightly vesicular. Contains occasional (≤ 1%) xenoliths of mafic material up to 6 cm (2.4 in) across. Correlates to intrusive andesite *Tii* of Seager (1986) and hornblende andesite and latite (*Krp*) of Hedlund (1977). Maximum thickness 54 m (177 ft).

Kwsm **Warm Springs quartz monzonite (upper Cretaceous)** – Light, whitish gray weathering brownish gray, ledge- to bouldery slope-forming, non- to slightly vesicular, occasionally dense, porphyritic, equigranular, fine- to medium-grained quartz monzonite. Weathers into angular to subangular slabs and boulders. Phenocrysts include 15-20% quartz (≤ 3 mm, anhedral), 9-12% biotite (0.5-2 mm, anhedral to subhedral; commonly weathered), 5-8% sanidine (1-4 mm, euhedral), and trace to 2% plagioclase (≤ 1.5 mm, anhedral). McLemore et al. (1999) dated this unit at 74.4 ± 2.6 Ma ($^{40}Ar/^{39}Ar$). Total thickness unknown.

Kcpm **Copper Flat quartz monzonite (upper Cretaceous)** – Porphyritic, fine- to medium-grained, plutonic quartz monzonite. Phenocrysts include 10-20% plagioclase (< 3 mm) and trace pyroxene and pyrite. Contains –ghost" crystals of hornblende and biotite. McLemore et al. (1999) dated this unit at 74.93 ± 0.66 Ma ($^{40}Ar/^{39}Ar$). Total thickness unknown.

Kau **Volcaniclastic deposits and lava flows on the northwestern side of Copper Flat, undivided (upper Cretaceous)** – Lava flows (labeled/assumed to be **Ka**) and dikes (**Ki**) in this area were determined using photogrammetry and have not be field checked due to restricted land access. **Kau** is likely dominated by volcaniclastic deposits with a few interbedded andesite flows.

Ka **Andesite flows and flow breccia of Copper Flat, undivided (upper Cretaceous)** – Grayish green to medium bluish or dark gray weathering dark grayish to reddish brown, porphyritic-aphanitic to porphyritic, fine- to coarse-grained andesite. Forms ledges or moderate to steep, rubbly slopes. Phenocrysts include 4-17% plagioclase, 0-8% hornblende, 0-5% biotite, and 0-5% pyroxene. Plagioclase phenocrysts up to 2 cm (0.8 in) are found in upper intervals. Lower flows are typically dense, with vesicularity increasing up-section. Propylitization along fractured surfaces to epidote is common. May contain xenoliths (and/or xenocrysts) of intermediate to silicic compositions. Flows are domed above the Copper Flat quartz monzonite stock or form the flanks of a stratovolcano (Seager, 1986). McLemore et al. (1999) dated an andesite flow at 75.4 ± 3.5 Ma (^{40}Ar/^{39}Ar). Hedlund (1977) cites the total thickness of andesite flows as 830 m (2723 ft) based on drill core data. Locally divided into 7 volcanic or volcaniclastic subunits:

Kax **Pyroxene-phyric andesite flows of Copper Flat** – Crystal-rich (15-20%) lava with conspicuous 5-7 mm pyroxene phenocrysts on weathered surfaces. Phenocrysts include plagioclase and potassium feldspar in addition to pyroxene. These lavas are exposed beneath **Tb** on Black Peak; contact metamorphism there caused copper mineralization in fractures in **Kax** on the east side of the peak. Dips south and is underlain by fine-grained andesite flows. Up to 35 m (115 ft) thick.

Kap **Plagioclase-phyric andesite flows of Copper Flat** – Gray weathering dark grayish brown, porphyritic, fine- to coarse-grained andesite. Forms ledges atop ridges of **Kaf**. Phenocrysts include 20-25% plagioclase (1-5 mm, subhedral to euhedral laths), 4-7% pyroxene (1-2 mm, anhedral; commonly altered to limonite or chlorite), and trace biotite (≤ 0.75 mm, subhedral). Contains 2-5% reddish lithic fragments (≤ 1 cm; may be overprinted by plagioclase phenocrysts) and trace to 3% disseminated magnetite. Non-vesicular and moderately foliated.

Kaf **Potassium feldspar-phyric andesite flows of Copper Flat** – Greenish gray weathering dull tannish gray, hypidiomorphic granular, fine- to very coarse-grained andesite. Forms ledges, steep rubbly slopes, and some hilltops on south side of Copper Flat. Phenocrysts include 15-17% sanidine (1-15 mm, euhedral, commonly as megacrysts), 6% plagioclase (1-2 mm, anhedral to euhedral), 2-3% pyroxene (0.5-1.5 mm, anhedral), and 1-2% hornblende (≤ 2 mm, euhedral laths). Dense/non-vesicular.

Kah **Hornblende-phyric andesite flows of Copper Flat** – Medium to dark gray weathering yellowish to reddish brown, porphyritic-aphanitic, fine- to medium-grained andesite. Forms small benches below **Kaf** and **Kap**. Phenocrysts include 3-8% hornblende (≤ 2.5 mm, subhedral to euhedral laths), 4-6% plagioclase (1-4 mm, subhedral to euhedral laths), and trace pyroxene (≤ 2 mm, anhedral). Somewhat dense/non-vesicular to slightly vesicular. Propylitization increase down-section. Plagioclase content may increase down-section where unit interfingers with **Kab** or **Kau**.

Kvs **Volcaniclastic debris flows of Copper Flat** – Greenish-gray debris flows with clasts that are light-colored, fine-grained, and altered light greenish-gray found only in Wicks Gulch. Most clasts are < 4 cm (1.6 in), though some (< 2%) are up to 0.5 m (1.6 ft) across. A few clasts are porphyritic lava with 3-4% pyroxene and plagioclase phenocrysts. The unsorted deposits are matrix supported and the clasts are angular. Maximum exposed thickness is 20 m (66 ft).

Kab **Laharic flow breccia of Copper Flat** – Dark purplish gray, mostly matrix-supported, massive, non-vesicular volcaniclastic breccia composed of angular to subangular pebble- and cobble-sized fragments. Pebble content increases to 95% up-section, where most fragments are subrounded. Middle and lower intervals contain fragments of 35-60% plagioclase-phyric and 40-65% hornblende-phyric andesite facies. Protruding fragments may result in rough weathered surfaces. Rarely exhibits weak trough cross-bedding with foresets up to 15 cm (6 in) high in finer grained intervals. Groundmass/matrix is typically aphanitic. May contain jumbled blocks of andesite 10s of meters across and may represent multiple episodes of clastic sedimentation based on changes in the dominant lithology of fragments and blocks. In places, (e.g. 264352E, 3649636N, UTM NAD83) this unit contains laminated, tabular, very fine- to fine-grained sandstone with angular volcanic grains with a few floating cobbles of porphyritic lava . The sandstone is locally cut by syn-depostional faulting and has pyrite mineralization. May interfinger with **Kaf**, **Kah**, and/or **Kau**.

Kb **Basaltic intrusion of Copper Flat** – Porphyritic intrusion. Crystal-rich with 10-15% Ca-plagioclase (< 2 mm). Minor pyroxene. Occurs in a dike and sill, the latter approximately 3 m (9.8 ft) thick.

Karst Fill

LPzkf **Karst fill (Cretaceous?)** – Localized, red deposits usually found in the Ordovician El Paso or Montoya formations that contain fragments of red siltstone, blocks (10s of meters across) of upper Paleozoic limestone and chaotically deformed Percha Shale in a red, silty matrix. Because one of the limestone blocks contains Pennsylvanian brachiopods (*Linoproductus* and *Derbyia*), the deposits likely formed after the Pennsylvanian. The red siltstone fragments are probably the Permian Abo Formation; thus the deposits are likely post-Permian in age. The sinkholes may have formed during the emplacement and mineralization of the plutons at Copper Flat. At least five deposits have been identified near the Percha Creek Box south of Copper Flat. The largest deposit on the east end of Percha Creek Box is about 300 to 400 m (984-1312 ft) in diameter and is at least 60 m (197 ft) thick.

Paleozoic bedrock

Pz **Paleozoic sedimentary rocks, undivided (Cambrian to Permian)** – Applied to strongly altered sedimentary blocks exposed in slivers along the Berrenda fault zone.

Pa **Abo Formation (lower Permian)** – Cross-section only. Reddish brown to light brown sandstone interbedded with grayish red shale and siltstone (Seager, 1986). Approximately 121 m (400 ft) thick in the Black Range; top is likely eroded in cross-section.

₽m **Magdalena Group (Pennsylvanian)** – Pink to brownish or greenish gray, very thin- to thick-bedded, massive, chert-free to somewhat cherty, sparsely fossiliferous limestone with subordinate siltstone, mudstone, and shale. Commonly wackestone or packstone. Fossils include bryozoans up to 13 mm across, echinoderm fragments 2-10 mm long, fusulinids and ostracods up to 3 mm in diameter, and the brachiopod *Linoproductus*. Strophomenids found in float near the Percha Creek Box are likely *Derbyia*. Cherty limestone with brachiopods common up-section. Bioturbated by horizontal burrows 1.5-2.5 cm (0.6-1 in) wide. Poorly exposed and/or altered to jasperoid, skarn, and marble along the margins of Copper Flat (McLemore et al., 2000). 130-255 m (427-837 ft) thick.

Mu Mississippian strata, undivided (lower Mississippian) – Cross-section only. Includes Lake Valley Limestone and Caballero Formation. Composite thickness 94 m (308 ft) in cross-section.

DM Devonian through Mississippian strata, undivided (upper Devonian through lower Mississippian) – Includes the Percha Shale and Lake Valley Limestone. Differentiated where identification of individual units is precluded by alteration to jasperoids or metamorphism to skarn or marble, or where access to exposures was denied. Found in northern quad.

Mlv Lake Valley Limestone (lower Mississippian) – Dark to light tannish or whitish gray, thin- to thick-bedded, massive to horizontally laminated, cherty, fossiliferous, occasionally marly limestone with subordinate siltstone and mudstone. Commonly packstone and grainstone. Occasionally features irregular wavy bedding. White to gray chert weathers to dark, orange-brown and occurs as crusts, lacy networks, and lenses up to 12 cm (4.7 in) thick and 60 cm (24 in) long. Fossils include crinoid stems up to 3 mm across, small (≤1 mm) echinoderm fragments, and brachiopods. Shell fragments may be silicified in places. Rare ostracods 0.75-1.5 cm (0.3-0.6 in) wide may occur in some beds, and domed, microbially induced sedimentary structures (algal mats) occasionally obscure bedding. Forms series of ledges and small cliffs above slopes of **Dp** in the Percha Creek Box area and above arenaceous to marly (O‘Neill et al., 2002) limestone of **Mc** in the southern part of the quad. Maximum thickness 84 m (276 ft). Locally subdivided into the crinoid-rich Nunn Member:

> **Mlvn Nunn Member** – Medium gray, thin- to medium-bedded, massive limestone with many large crinoid fragments and rare chert nodules. Abundance of crinoids gives unit the appearance of a crinoid ―hash.” May contain subordinate ostracods and miscellaneous echinoderm fragments. Often marly and coarsely crystalline (O‘Neill et al., 2002). Maximum thickness 36 m (118 ft).

Mc Caballero Formation (lower Mississippian) – Dark gray, medium- to thick-bedded, massive to cross-stratified or laminated, cherty, fossiliferous limestone. Lamination observed in uppermost 1.2 m (3.9 ft). Commonly an arenaceous to marly packstone (O‘Neill et al., 2002). Chert occurs as dark colored masses and networks. Fossils include crinoid and other echinoderm fragments. 8-10 m (26-33 ft) thick.

OSD Ordovician through Devonian strata, undivided (lower Ordovician through upper Devonian) – Includes the El Paso Formation, Montoya Formation, Fusselman Dolomite, and Percha Shale. Differentiated where identification of individual units is precluded by alteration to jasperoids or metamorphism to skarn or marble. Mapped in absence of upper Paleozoic carbonates (**Mc**, **Mlv**, and **Pm**), typically in fault zones.

Dp Percha Shale (upper Devonian) – Dull grayish green to yellowish gray to black, fissile, calcareous shale. Interbeds with light purplish gray, very thinly bedded to laminated, non-calcareous siltstone. Forms moderate to steep slopes below ledges and small cliffs of **Mlv** in the Percha Creek Box area. Fossiliferous in its upper ~15 m (49 ft), containing fenestelloids and other bryozoans, as well as numerous brachiopods, including *Schizophoria australis* and *Petrocrania* sp. Features limestone nodules 3-14 cm (1.2-5.5 in) in diameter in upper 6-10 m (20-33 ft). Maximum thickness 45 m (148 ft).

OS Ordovician through Silurian strata, undivided (lower Ordovician through lower Silurian) – Includes the El Paso Formation, Montoya Formation, and Fusselman Dolomite. Differentiated where identification of individual units is precluded by alteration to jasperoids or metamorphism to skarn or marble. Mapped where Percha Shale is conspicuously absent.

Sf Fusselman Dolomite (lower to middle Silurian) – Light to dark gray, thin- to thick-bedded, massive to weakly laminated, sparsely fossiliferous, cherty, dolomitic wackestone. Forms a series of ledges and slopes. Purplish gray chert weathers orange to reddish brown and occurs in veins, crusts, lenses, and beds 1-7 cm (0.4-2.8 in) thick. Less chert occurs in the upper part of the formation. Fossils include occasional brachiopods 1-3 cm (0.4-1.2 in) wide that are commonly silicified. Brecciated jasperoid beds near the top of the formation may be associated with slippage along the contact with ductile **Dp**, forming a cap to fluid migration (O'Neill et al., 2002). Maximum thickness 22 m (73 ft).

€O Cambrian through Ordovician, undivided (upper Cambrian through upper Ordovician) – Includes the Bliss Formation, El Paso Formation, and Montoya Formation. Differentiated where identification of individual units is precluded by alteration to jasperoids or metamorphism to skarn or marble.

O Ordovician strata, undivided (lower to upper Ordovician) – Ordovician strata exposed in the Hillsboro quadrangle commonly feature pervasive alteration to jasperoid, skarn, or marble (McLemore et al., 1999). Brecciated jasperoids containing clasts of limestone and chert are common south of Copper Flat in the vicinity of the Percha Creek Box. Where these rocks are unaltered, they may be whitish to very dark gray, thin- to medium-bedded, commonly wavy bedded dolostone and limestone. Wackestone is common. Total thickness 286 m (938 ft) in Lake Valley-Hillsboro area (Hedlund, 1977).

Om Montoya Formation (middle to upper Ordovician) – The base of the Montoya Formation is marked by the 3 to 12 m (10-39 ft) thick Cable Canyon Sandstone, a poorly-sorted quartz arenite with angular, very fine to fine grains and ~5% subrounded, medium grains. The sandstone is usually overlain by dark gray weathering light orange gray, thin-bedded, tabular, massive, sparsely fossiliferous, sparsely cherty dolostone. The latter commonly contains packstone. Chert occurs as crusts. South of Copper Flat, cherty dolostone just above the Cable Canyon Sandstone is commonly altered to a strata-bound jasperoid composed of angular, pebble-sized, chert fragments. Elsewhere, particularly along the contact with one of the Copper Flat intrusions along Animas Gulch, the dolostone is metamorphosed to marble. Contains solitary coral and few brachiopods. Hedlund (1977) assigns the Montoya Formation a total thickness of 140 m (459 ft).

Oep **El Paso Formation (lower Ordovician)** – Medium to dark gray weathering dark purplish gray, thin- to thick-bedded, tabular, cherty, somewhat fossiliferous, limestone to limey mudstone. Packstone is common. Chert is laminated and pink to red in places. Fossils include gastropods, small bryozoans and sponges up to 8 mm across, occasional ostracods up to 3 mm across, and horizontal burrows up to 12 mm wide. Chert occurs in lacy networks. The El Paso below the Cable Canyon Sandstone has gastropods, horn coral, stromatolites, and tiny brachiopods. The El Paso just above the Bliss sandstone has burrows and poorly preserved brachiopods. Total thickness of 146 m (479 ft) in Lake Valley-Hillsboro area (Hedlund, 1977).

ЄOb **Bliss Formation (upper Cambrian to lower Ordovician)** – Very dark bluish gray weathering purplish brown, well indurated, tabular, horizontally to ripple cross-laminated, very well sorted, subrounded to rounded, very fine- to fine-grained quartzose sandstone. May be a quartzite with a poorly sorted sandstone protolith containing 95% quartz and 5% altered grains. Features common vertical burrows (likely *Skolithos*) 1-5 cm (0.4-2 in) wide, occasionally replaced by chert. Maximum thickness ~40 m (130 ft).

Precambrian basement rock

pЄ **Proterozoic rocks, undivided (Paleo- to Mesoproterozoic?)** – Cross-section only. Includes granite, gneiss, and schist.

pЄg **Granite (Mesoproterozoic?)** – Pink to red, medium-grained granite containing quartz, feldspar, and biotite.

pЄs **Quartzofeldspathic gneiss of Tank Canyon (Paleoproterozoic?)** – Pale brownish gray, fine- to medium-grained gneiss containing 70% sericitized albite and 30% quartz. May contain accessory biotite and ferric oxide minerals. Features thin layers of hornblende schist that strike parallel to foliation observed in aggregated quartz granules (Hedlund, 1977).

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