## Contents

# 1. Executive Summary

The Cubero quadrangle lies along the Rio San Jose south of Mount Taylor in the southeastern corner of the Colorado Plateau physiographic province. Sedimentary geologic units exposed on the quadrangle range in age from Upper Jurassic to Holocene with substantial unconformities spanning the Early-Middle Cretaceous and the Paleocene through Miocene. The Jurassic System is represented by the dominantly-eolian Zuni Sandstone and the overlying, dominantly-waterlain Morrison Formation. On this quadrangle, a sequence of intercalated fluvial and eolian sandstones located stratigraphically below the pebbly sandstones of the Westwater Canyon Member of the Morrison appear to be separated from the Morrison by an unconformity, and also appear to be lithologically similar to the underlying Zuni Sandstones, and hence are assigned to the Zuni as a fluvial facies, and not to the Recapture Member of the Morrison. The bulk of the Morrison Formation exposed in the quadrangle is assigned to the Brushy Basin Member.

The Cretaceous System is represented by intercalated Upper Cretaceous deposits of the Mancos Shale and Dakota and Gallup Sandstones, overlain by the heterolithologic Crevasse Canyon Formation. In ascending order, the units present are: Encinal Canyon Member (Dakota); Oak Canyon Member (Dakota); Cubero Sandstone Tongue (Dakota); Clay Mesa Shale Tongue (Mancos); Paguate Sandstone Tongue (Dakota); Whitewater Arroyo Shale Tongue (Mancos); Twowells Sandstone Tongue (Dakota); a lower "main body of the Mancos" (includes the Bridge Creek Limestone Member); an upper "main body of the Mancos" (includes the Semilla Sandstone Member); the "F", "E", and "C" tongues of the Gallup Sandstone and intercalated unnamed tongues of the Mancos; the Dilco Member and Borrego Pass Lentil ("stray sandstone") of the Crevasse Canyon Formation; and, finally, the Mulatto Shale Tongue (Mancos).

The Cretaceous System is overlain with angular unconformity by Pliocene to Holocene basalts and alluvial deposits. The Pliocene through Middle Pleistocene history is marked by progressive incision of the Rio San Jose and its tributaries, and hence the oldest Cenozoic deposits occupy the highest topographic levels. Pliocene-Early Pleistocene basalts occur beneath high mesas extending into the northern margin of the quadrangle from the Mount Taylor volcanic field to the north; these are locally underlain by Pliocene pediment gravels. The Early Pleistocene Flower Mountain basaltic volcano lay near the center of the quadrangle, overlying ancestral Rio San Jose and tributary alluvium. Inset against the Flower Mountain volcano are at least five levels of alluvial fan and terrace deposits. Older fan deposits are highly eroded and represented by discontinuous remnants at high levels capping low hills in the valley south of Mount Taylor. Older terrace deposits occur as discontinuous sandy gravel deposits forming low mounds on Dakota Sandstone-capped mesas to the south and north of the modern Rio San Jose. Younger fan and terrace deposits underlie the modern piedmont and valley floor. By the junction of Cañon Seama and the Rio San Jose, a basalt flow occurs at depth intercalated with alluvial fill that is correlated to the Middle Pleistocene Laguna Pueblo flow, providing local age control.

Mesozoic strata generally dips shallowly to the north, with local perturbations usually associated with nearby faults. Late Cenozoic deposits are subhorizontal. Facture patterns and map patterns in an exposure of the northeast-trending Woods Mesa fault suggests the fault accommodated left-lateral-reverse oblique slip, suggesting the fault was formed by Laramide transpressional deformation. The fault (and associated monoclinal fold) can be observed deforming strata only as young as the Cubero Sandstone Tongue. In contrast, an exposure of an east-west-striking fault to the south of the Woods Mesa fault shows evidence of normal dip-slip; this fault may have formed during Oligocene-to-Quaternary extension.

Dikes of north-south and northwest-southeast orientation are found throughout the study area. One of the northwest-southeast dikes, the Acomita dike, was K-Ar dated to the Oligocene, and thought to reflect northeast-southwest-directed extension associated with the early Rio Grande rift. The north-south dikes may reflect later east-west-directed extension.

# 2. Introduction

## 2.1. Geologic and geographic setting

The Cubero quadrangle lies a few tens of kilometers (km) east-southeast of the town of Grants along I-40 in northwestern New Mexico, and includes the communities of Seama, Acomita, San Fidel, and Cubero, among others. Portions of the quadrangle lie on the Cubero Land Grant and the Pueblos of Laguna and Acoma. The Rio San Jose river valley roughly bisects the quadrangle along an east-west transect. The northern half of the quadrangle is underlain mainly by broad, low-relief valleys graded from the mouths of the canyons that drain the southern and southeastern flanks of Mount Taylor down-gradient southward to the Rio San Jose valley. Some higher relief terrain occurs along the northern margin of the quadrangle associated with the southern edge of the Mount Taylor highland. The southern half of the quadrangle is underlain by broad mesas overlooking alluvial valleys. Elevations range from about 1,808 meters (m) above mean sea level (amsl) where the Rio San Jose exits the quadrangle to a high of about 2,237 m amsl on the top of a basalt-capped mesa extending onto the quadrangle from Mount Taylor.

Geologically, the quadrangle lies in the Acoma Sag section of the Colorado Plateau between the Rio Puerco fault zone and the McCartys syncline (Woodward, 1982), along or just south of the Jemez lineament and to the south and east of the Mount Taylor and Zuni-Bandera volcanic fields, respectively. The majority of the quadrangle is underlain by clastic Mesozoic strata with a variable thickness of Quaternary alluvial cover. This cover is particularly thick along the Rio San Jose, Cañon Seama, and the broad valley north of I-40. Local Plio-Pleistocene basaltic volcanic rocks cap high mesas and underlie Flower Mountain. Structural relief is generally low.

## 2.2. Previous work

Early studies concerning the Cubero area include the reconnaissance work of Dutton (1885) and mapping of the Mount Taylor coal field by Hunt (1936). A concerted geologic mapping and stratigraphic study effort was performed in the 1960's through 1980's by the United States Geological Survey (USGS) in support of uranium resource development. Maxwell (1990) mapped the Cubero quadrangle during this period (1970-71), utilizing the stratigraphy established previously by Dutton, Hunt, and mappers on surrounding quadrangles as well as by new research by Landis et al. (1973). Hook et al. (1983) and Molenaar (1983) would subsequently further refine the Cretaceous stratigraphy above the Dakota Sandstone, while S.M. Condon (Condon, 1989; Condon and Huffman, 1988; Condon and Peterson, 1986) and O.J. Anderson and S.G. Lucas (Anderson, 1993; Anderson and Lucas, 1992, 1995) would propose competing revisions to the Jurassic stratigraphy.

Largely simplified in earlier geologic studies, the Cenozoic section received renewed interest in the 1980's and 1990's as a part of larger-scale studies of the volcanic and landscape history of the Mount Taylor and Zuni-Bandera areas (e.g., Drakos et al., 1991; Laughlin et al., 1993). Refinement of this chronology continues sporadically to this day (e.g., Cascadden et al., 1997; Channer et al., 2015; Dunbar and Phillips, 2004; Goff et al., 2015; Laughlin and WoldeGabriel, 1997).

More recent geologic mapping efforts by the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) concentrated on the Mount Taylor area (synthesized by Goff et al., 2015) and subsequently proceeded down the Rio San Jose from Grants. This report synthesizes these previous studies with original geologic mapping from the 2015-16 season to provide an up-to-date geologic product for the Cubero quadrangle.

## 2.3. Acknowledgements

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# 3. Stratigraphy

Geologic terms after Compton (1985), soil terms after Birkeland (1999), carbonate horizon stages after Gile et al. (1966) and Machette (1985), and color notation after Munsell Color (2009). Coordinates given in figure captions are Universal Transverse Mercator (UTM) coordinates after the NAD83 Zone 13S datum.

## 3.1. Miscellaneous units

### 3.1.1. Artificial fill (af)

Artificial fill consists of variably compacted muds, sands, and gravel underlying roadways, railroads, and dams. Unit is only mapped where the fill is particularly thick, or where it obscures underlying geologic relationships. Thickness up to about 10 m.

### 3.1.2. Landslides, debris flows, and colluvium (Qls, Qc)

Surrounding many sandstone- and basalt-capped mesas in the area are thick sections of landslide and colluvial material. Landslide terrains (Qls) consist of poorly sorted muds to boulders transported downslope as coherent or partially coherent blocks. Blocks commonly display evidence of both translational and rotational displacement. Map unit contains significant colluvium and lesser locally-derived alluvium. Some basaltic landslide blocks are found on the distal piedmont at relatively great distances from the present edge of high basalt-capped mesas. These are interpreted to be ancient landslide remnants which originated as toreva blocks or rotational slides from mesas that extended much further toward the axis of the Rio San Jose valley in early Pleistocene time. Blocky basalt underlain by and/or jumbled chaotically with Cretaceous sandstone blocks and minor gravel from map unit Tpal form local caprock over more erodible shale units. Landslide deposit thicknesses may be as much as 60 m.

Colluvium (Qc) consists of poorly sorted muds to boulders transported by mass wasting and unconfined alluvial processes. Map unit also includes substantial fine sandy eolian material incorporated into the mass wasting product. Unit is only mapped where extensive, particularly thick, or where obscuring underling geologic relationships. Thicknesses may exceed 15 m.

### 3.1.3. Eolian and slopewash material (Qes, Qasw)

Fine-grained slopewash and eolian deposits are locally mapped where particularly thick, usually as a result of local topographic impoundments such as the edges of rotated landslide blocks. Eolian deposits (Qes) are up to 3 m thick of well-sorted, rounded to subrounded, very fine- to fine-grained quartz sand with minor lithics. Soil development consists of A/C horizonation, locally burying a weak carbonate horizon (Stage I Bk) with 7.5YR color (Table 1). Slopewash deposits (Qasw) are principally fine-grained fills that accumulate behind large landslide blocks to form low-relief benches.

## 3.2. Ancestral and modern Rio San Jose valley deposits

Mapping of alluvial surficial deposits follows the style and terminology developed by Grimm (1983), Drakos et al. (1991), and Osburn et al. (2009). The Plio-Pleistocene stratigraphy in the Mt. Taylor area includes one Pliocene unit and four widespread Quaternary units that lie above the modern floodplain or arroyo floor. In the Cubero quadrangle, Pliocene deposits (unit Tpal, below) are limited to pediment deposits that cap an erosional surface cut on Cretaceous sedimentary rocks, and overlain by volcanic units on the middle mesa. Axial ancestral Rio San Jose deposits and associated tributary or pediment gravel facies underlying Flower Mountain were formerly mapped as Pliocene deposits but now fall within the early Pleistocene Epoch with the change in the Plio-Pleistocene boundary from 1.8 to 2.5 Ma.

The Pliocene and Quaternary deposits and associated geomorphic surfaces in the Mt. Taylor area record a history of long-term incision interrupted by periods of base level stability. In contrast to the overall Plio-Quaternary history, the late Quaternary has been characterized by alternating periods of erosion and deposition. Approximately 200-300 m of incision has occurred into the Pliocene pediment surface between 2.5 m.y. and the present time, likely in response to regional uplift. Periods of erosion and deposition during the late Quaternary are likely in response to climatic fluctuations, continued regional uplift, and/or episodic volcanism in the Zuni Bandera volcanic field periodically blocking drainages (Drakos and Riesterer, 2013).

### 3.2.1. Post-Flower Mountain volcano alluvium

Post-Flower Mountain sediments include fluvial terrace, alluvial fan deposits, and valley floor alluvium. Quaternary deposits contain a predominance of volcanic clasts of mixed lithologies, secondary Cretaceous sandstone clasts, and minor chert pebbles. Fan units Qf1-Qf4, mapped in the northern third of the quadrangle, form the distal part of a fan complex at the mouth of Water, Timber, Castillo, Seco, and San Jose Canyons. Deposition of the Water Canyon fan, which began by early Pleistocene time (correlative fine-grained deposits exhibit reversed polarity: Drakos et al., 1991), record incision into the volcanic edifice, erosion of the amphitheater on Mt Taylor, and episodic piedmont aggradation, incision, and stabilization (Drakos and Riesterer, 2013). The piedmont has been extensively dissected since initial fan deposition, therefore Qf1 surfaces are preserved as relatively small remnants and Qf2 is preserved as larger surfaces. Much of the modern piedmont in the distal part of the fan complex is composed of the middle to late Pleistocene Qf3 and Holocene Qf4 surfaces. The Qf3 map unit includes a thin (less than 1 m thick) veneer of younger fan deposits overlying Qf3 deposits throughout much of the Cubero quad. Aggradation of Qf3 (and overlying Qf4) is likely a result of aggradation along the Rio San Jose drainage associated with eruption of the 0.38 to 0.128 Ma Laguna Pueblo flow (Champion et al., 1988; Channer et al., 2015; Lipman and Menhert, 1979), which flowed down the Rio San Jose drainage.

Deposits underlying terrace surfaces along the Rio San Jose are preserved as isolated erosional remnants north and south of the modern Rio San Jose drainage. Qt1 includes axial Rio San Jose gravel and tributary gravel facies approximately 7 m thick, and overlies the Cubero Sandstone Tongue of the Dakota Sandstone on Woods Mesa south of the Rio San Jose. Qt2 is a fill terrace approximately 12 m thick comprising interbedded bedded sand and channel-fill gravel deposits overlying the Cubero Tongue north of the Rio San Jose. Qt3 includes two small erosional remnants overlying the Oak Canyon Member of the Dakota Sandstone. Qf1-Qf3 fan units appear to be graded to Qt1-Qt3 Rio San Jose terraces. The valley floor alluvium is composed primarily of fine-grained sand, silt and clay with gravel lenses. Thicknesses of various alluvial deposits, based on well log data (Risser and Lyford, 1983) and outcrop descriptions, range from 5 to 20 m in tributary drainages to approximately 50 m under the Rio San Jose valley floor near the confluence with Cañon Seama. Rio San Jose alluvium includes coarse-grained sandy gravel sections and is interbedded with a 12 to 18 m thick basalt flow (the Laguna Pueblo flow: see discussion in “Volcanic structures” section below), encountered 12 to 15 m below the valley floor (Channer et al., 2015; Drakos et al., 1991; Risser and Lyford, 1983).

*Qal*

Deposits of sand, silt, and gravel in valley bottoms (**Figures 3.2-1 and 3.2-2**); upper 5-10 m of Qal deposits are Middle to Late Holocene in age; older, buried alluvial deposits in Rio San Jose valley are Pleistocene in age. Alluvium is typically fine-grained, silt and sand with pebble- and cobble-gravel lenses and interbedded colluvium in tributary drainages (FIGURE 3.2-2). Deposits are characterized by weakly-developed soils with 10YR-7.5YR color (reflecting varying parent material), none to Stage I carbonate morphology, and a lack of Bt horizon development (Table 1). Rio San Jose alluvium includes coarse-grained sandy gravel sections.

*Qt4*

Limited to a single deposit on the northern margin of the quadrangle near the mouth of Cañon Seco. Qt4 deposits described on the adjacent Mt. Taylor quadrangle consist of sandy pebble- to boulder-size gravel underlying terrace surfaces located approximately 3 to 5 m above local base level. Deposit thickness ranges from 2 m to greater than 6 m. Soils developed in deposits underlying Qt4 surfaces are weakly developed, with 10YR color, minimal horizon development, none to minimal carbonate accumulation, and lack a Bt horizon. Middle to Late Holocene in age.

*Qt3sj*

Deposits of sandy pebble- to boulder-size gravel underlying small eroded remnants of terrace surfaces located approximately 20 m above Rio San Jose valley floor/local base level. Middle (?) Pleistocene in age.

*Qt2sj*

Deposits of sandy pebble- to boulder-size gravel and interbedded well-sorted, rounded-subangular, medium-coarse-grained, parallel-to-low-angle cross-bedded quartz lithic sand (~85% quartz, 15% lithics) underlying fill terrace surfaces located approximately 50 m above Rio San Jose valley floor/local base level. Clast composition consists of 70-80% volcanics (typically cobble-to-boulder-sized clasts of basalt, andesite, dacite, rhyolite), with lesser sandstone, chert, shale, and minor quartzite and granite. Deposit thickness is approximately 10 m. Surface is stripped and soils are poorly preserved. Middle (?) Pleistocene in age.

*Qt1, Qt1sj*

Deposits of subrounded to rounded sandy pebble- to cobble-size gravel located 70 to 75 m above Rio San Jose valley floor; deposit thickness is approximately 7 m. Interpreted as eroded fluvial terrace remnants. Qtsj is an axial ancestral Rio San Jose deposit with abundant quartzite, chert, and volcanic clasts including basalt and rhyolite, with subordinate granite and limestone cobbles. Qt1 is a tributary facies comprising poorly sorted, subrounded, basalt and disc-shaped clasts of sandstone, with quartzite clasts and common reworked Cretaceous shell fragments. Carbonate-cemented throughout upper 1-2 m of deposit, indicating that the original deposit was capped by a calcic or petrocalcic soil. Early(?) Pleistocene in age.

*Qfy*

Typically fan-shaped deposits of coarse bouldery gravel and sand, silt, and clay that emanate from tributary drainages along the axes of major drainages. Grades into alluvial deposits along main channels; probable late Holocene age.

*Qf4*

Part of a fan complex at the mouth of Water, Timber, and Castillo Canyons; Qf4 surfaces form part of the modern piedmont. Deposits of fine sand to coarse gravel; typically interbedded fine to medium sand and imbricated cobble-to-boulder-size gravel with individual gravel beds 0.25 to 3 m thick. Qf4 deposits typically include buried soils. Base of deposit poorly exposed; total thickness 2 to 10 m or more. Qf4 soils are characterized by cambic (Bw) or weakly-developed carbonate (Bk) horizons, with maximum Stage I+ carbonate morphology; locally include buried Bw or Bk horizons (Table 1). Holocene.

*Qf3*

Part of a fan complex at the mouth of Water, Timber, Castillo, Seco, and San Jose Canyons; Qf3 surfaces form part of the modern piedmont. Deposits of sandy pebble to boulder gravel of mixed volcanic lithologies and subordinate sandstone clasts greater than 3 m thick; base of deposit poorly exposed. Throughout the Cubero quad, Qf3 deposits are overlain by less than 1 m of young (Qfy or Qf4) alluvium (**Figure 3.2-3**, Table 1). Where Qf3 deposits are overlain by thin alluvial deposits they are mapped as Qf3. Soils are partially eroded, but exhibit Stage II to III carbonate morphology and Bt horizons with 5YR to 7.5YR color (**Figure 3.2-3**, Table 1). Likely Middle Pleistocene.

*Qf2*

Deposits of rounded to subangular sandy pebble to boulder gravel underlying remnant fan surfaces at the mouths of Timber, Castillo, and San Jose Canyons, including a large fan surface at the mouth of San Jose Canyon (**Figure 3.2-4**). Deposit is 6 to 10 m or more thick. Qf2 fan surfaces are 13 to 15 m above local base level. Soils are stripped; however, clasts eroding from the deposit exhibit continuous carbonate coatings. Likely Middle Pleistocene.

*Qf1*

Deposits of rounded to subangular sandy pebble to boulder gravel underlying small remnant fan surfaces between the Seco and Castillo Canyon drainages. Deposit is partially eroded; remnants are 4 to 6 m thick, predominantly basalt plus andesite, dacite, and ~5% sandstone gravel. Qf1 fan surfaces are 30 to 35 m above local base level. Soils are stripped; however, clasts eroding from the deposit exhibit continuous carbonate coatings on one or multiple sides. Early(?) Pleistocene age.

### 3.2.2. Flower Mountain alluvium and basalts

Just east of the center of the quadrangle lay Flower Mountain, a narrow cinder cone remnant with associated outflow basalt capping a low mesa. Flower Mountain has received passing notice in several geomorphic/geochronologic studies due to its landscape position in between the present-day Rio San Jose valley and the higher and older basalt-capped mesas to the north surrounding Mount Taylor (cf., Channer et al., 2015; Drakos et al., 1991; Laughlin et al., 1993), but relatively little detailed mapping for the area was found (cf., Maxwell, 1990). The Mountain received considerably more attention in this mapping effort, in large part because of the recognition of ancestral Rio San Jose and tributary alluvium underlying (and inset upon by) the volcanics. Laughlin et al. (1993) published a K-Ar age of 2.390 ± 0.114 Ma for the "lowermost flow," while Channer et al. (2015) determined a $^{40}Ar/^{39}Ar$ age of 1.888 ± 0.012 Ma. Neither publication precisely located the analyzed sample, hence neither age can be assigned to any of the map units presented below with confidence.

*Basalt of Flower Mountain (Qbf)*

The flat-topped mesa portion of Flower Mountain is capped by the basalt of Flower Mountain, a medium to dark gray, weathering black and brownish gray, finely porphyritic basalt. Visible crystals cover 10 to 15% of fresh surfaces, mostly <1 mm across but 1-2% are above 1 mm diameter. Phenocrysts include pyroxene, olivine, and plagioclase, most of which are degraded and anhedral, precluding accurate assessment of modal abundances from hand specimens and hand lenses. Very sparse outsized "megacrysts" up to 1.5 cm across are generally pyroxene. The bulk of the basalt is solid with sparse vesicles, well columnar jointed, and weakly or moderately flow-foliated. Sparse granitic xenoliths are up to 4 cm across. In outcrop, the flow is up to about 12 m thick, but appears to thin to a pinchout at the west extent, possibly due to underlying paleotopography. The basalt flow can be observed in outcrop to overlie Qbfp, and appears to at least partially overlie Qbfc in a gully just northeast of the Flower Mountain peak, which would imply the basalt flow is the youngest deposit in the eruptive sequence.

### *Cinder of Flower Mountain (Qbfc)*

Flower Mountain itself is underlain by a cinder cone developed over the vent area for the volcanic sequence. The cone consists dominantly of dark reddish brown or dark gray to black scoriaceous basaltic pyroclasts ranging from 1 mm to 1 m in diameter. Basaltic material is mainly aphanitic but with sparse vitreous pale greenish phenocrysts <1 mm in diameter that are most likely pyroxene or olivine. Vesicles are variably filled with calcite, as is the inter-pyroclast porosity. Outcrops are variably foliated. Very locally, dikes and possible sills or welded spatter horizons are found cutting and/or intercalated with the cinder. Sparse gneissic xenoliths up to 30 cm across can be found throughout, and at the base of the cinder deposit there are additionally xenoliths of altered brecciated quartzose sandstone as well as rounded pebbles of sandstone, granite, chert, limestone, and volcanics possibly derived from ancestral Rio San Jose gravels. Locally, deformed mudstones, similar to nearby Mancos Shale outcrops, are also found (**FIGURE 3.2-5**), which may explain an anomalous outcrop of shale found at the top of a gully to the west of the Flower Mountain peak (**FIGURES 3.2-6 AND 3.2-7**). The exposure is poor, but the available outcrop appears to show a section of Mancos Shale lying between a lower outcrop of Qbfp and an upper outcrop of Qbfc. Alluvium is found underlying the Qbfp outcrop further down the gully. The shale is either a paleo-hill inset upon by over 100 ft of alluvium and basal volcanics that was subsequently buried by cinder, or is large Mancos xenolith. The cinder cone deposit is up to 90 m thick. Cinder of Qbfc can be found in outcrop directly overlying Qbfo and Qbfp, and some Qbfc outcrops appear to underlie Qbf.

### *Older basalt of Flower Mountain (Qbfo)*

Along the eastern and southern flanks of Flower Mountain, the reddish brown scoriaceous cinder overlies medium to dark gray flow breccia which overlies solid "spotted" basalt. This basalt is light to medium gray to light brownish gray, though variably stained light reddish brown or light brown by oxides. Common to abundant pale gray rounded "spots" up to 2 cm across are found particularly along weathered surfaces (**FIGURE 3.2-8**). Phenocrysts up to 2 mm in diameter occupy 5-15% of fresh surfaces, but are generally anhedral and reduced to light reddish brown clots (iddingsite?). Locally, these reddish brown clots have black cores of possibly remnant pyroxene, and very locally black anhedral preserved pyroxene phenocrysts up to 4 mm across are present. The matrix of the basalt is granular, with common vitreous clear crystal facies (plagioclase?) imparting a specular appearance under a hand lens. Sparse gray gneissic xenoliths are present throughout the basalt. Outcrops are variably fractured, grading from massive and solid to highly fractured and locally internally brecciated at the southern tip of exposure. The unit is up to 40 m thick in outcrop.

Qbfo is interpreted to be a separate basalt from Qbf because the two basalts are texturally distinct and because Qbfo demonstrably underlies Qbfc, while Qbf appears to overlie at least some of Qbfc. The "spotted" texture of Qbfo is similar to that of Qbfd, the map unit of the dikes seen underlying the cinder cone. Qbfo could be interpreted as either an early, pre-cinder cone flow from the same vent area, as a part of a volcanic neck (*sensu* Hallett, 1992), or as a solidified magma pool associated with the cone (cf., Crumpler, 2003).

### *Basaltic dikes of Flower Mountain (Qbfd)*

At least two dikes underlie the southwestern flank of Flower Mountain, both of which are texturally similar. Both dikes are light to dark gray, weathering to brownish gray, with 10-15% visible phenocrysts up to 1 mm across of anhedral pyroxene (variably degraded to dark reddish brown iddingsite[?]) and subhedral plagioclase; the thinner northern dike also has very sparse larger anhedral pyroxene phenocrysts up to 0.5 cm across. Both dikes have an aphanitic matrix that is finely granular under a hand lens, and both bear rare to locally abundant pale gray "spots" on weathered surfaces like those described above under Qbfo. Both dikes also contain sparse granitic and gneissic xenoliths up to 14 cm across and exhibit subvertical fracturing or foliation. The thinner northern dike is 5-10 m thick and trends east-northeast, while the thicker southern dike is 25-30 m thick and trends north-northeast. The thinner northern dike clearly intrudes pre-Flower Mountain ancestral Rio San Jose and tributary alluvium. The southern thicker dike is surrounded by colluvium. Both dikes appear to merge upslope with outcrops of Qbfo basalt, with which the dikes are texturally similar.

#### *Pyroclastics of Flower Mountain (Qbfp)*

On all sides of Flower Mountain, massive to bedded basaltic pyroclastic deposits are locally found underlying Qbf and Qbfo basalts. Beneath Qbf along the northeastern, northern, and western flanks of the basalt-capped mesa, these pyroclastics consist of massive or poorly bedded ash underlying a sequence of massive lapilli overlain by well bedded and cross-bedded lapilli (**FIGURE 3.2-9**). The massive ash is pale brown (2.5Y 7/3 measured) and composed mainly of glassy clasts <1 mm across with sparse clasts up to 2 mm across. The later are identifiable as variably weathered scoriaceous basaltic material. Exposed thickness is up to 0.5 m. Above the ash is ~10 cm of massive lapilli overlain by up to 30 cm of first normally graded then reverse graded lapilli. Interval is overlain by up to 30 cm of well bedded and cross-bedded lapilli. Lapilli through this interval are 2 to 30 mm across, with sparse outsized bombs up to 40 cm across, that are subrounded to rounded, clast-supported and matrix-poor, and consist of medium to dark gray vesicular basalt. Pyroclastics exposed to the southwest of the Flower Mountain peak are similar, though the bedded interval is less well-structured. Here, the unit is up to about 3 m exposed thickness.

Due south of the Flower Mountain peak, the unit exhibits a somewhat different character, consisting of a thick section of massive to weakly bedded lapilli tuff with variable degrees of weathering evident in the ashy matrix and lapilli clasts (**FIGURE 3.2-10**). Lapilli clasts are rounded vesicular basaltic material mostly (99%) under 30 mm in diameter but with outsized bombs up to 10 cm across, that are variably unweathered medium to dark gray and degraded light yellowish brown colors. Chalky white siliceous blocks, either ashy lithics or chert xenoliths, are <1-1% of clasts, and very sparse xenoliths of pale gray gneissic material, beige and light gray sandstones, pinkish granites, rounded varicolored cherts, and rounded limestones are also present. Xenoliths and lapilli are clast-supported. Matrix ashes are pale brown to light reddish brown in color, and generally very fine-grained with sparse glassy aggregates up to 0.5 mm across.

The pyroclastic outcrop is surrounded by colluvium, but appears to be inset into underlying alluvial deposits and Mancos Shales and partially inset into the top of the Cubero Sandstone Tongue. Given the presence of alluvium, the possibility exists that the Flower Mountain magmatic system encountered shallow groundwater and explosively excavated a hydromagmatic crater (maar) that backfilled with this pyroclastic material early in the formation of the Flower Mountain volcano. Alternatively, this pyroclastic section may be a later phase of pyroclastic breccia filling the cinder cone pipe and be a part of a volcanic neck (*sensu* Hallett, 1992). Exposed thickness is as much as 90 m.

*Alluvium underlying Flower Mountain (Qafm)*

Underlying the volcanics of Flower Mountain is a sequence of ancestral Rio San Jose and tributary alluvium locally exposed to the south of the Flower Mountain peak and in landslide blocks along the east side of the mountain. The bulk of the alluvium is tributary alluvium, which consists dominantly of poorly sorted muddy fine to medium sands with scattered gravel (**Figure 3.2-11**). Sands vary in color from pink to pale brown to light yellowish brown and locally light gray (7.5YR 7/3, 6/4, 8/3; 10YR 7/3, locally 6/6; and 2.5Y 7/2 measured) and consist dominantly of poorly sorted very muddy vfL to mL grains of principally rounded quartz with common medium to dark gray (basaltic) and pink (siliceous) lithics. Local lenses of medium to coarse sand grains contain more abundant chalky white (chert?), light reddish brown (basaltic), and dark gray (basaltic) lithics. Clayey mudballs up to 30 cm across are locally common (**Figure 3.2-12**), and one location the sands are variably stained light orangish brown by oxides. Unit grades up into coarse-grained pyroclastics. Exposed thickness of alluvium is up to about 3 m.

*Ancestral Rio San Jose alluvium underlying Flower Mountain (Qsjf)*

Interbedded with the tributary alluvium is up to 1.5 m of moderately well indurated extrabasinal rounded gravel of lithologies that appear to reflect the Zuni Mountains to the west that are interpreted to be the deposits of an ancestral Rio San Jose (**Figure 3.2-13**). Gravel are poorly sorted clast-supported pebbles and cobbles (max of ~15 cm diameter) of dominantly rounded cherts and quartzose sandstones; lesser but common granites; rare basalt, quartzite, and limestone; and sparse dark brownish gray pyroclastic clasts. The matrix is pale brown to light reddish brown (7.5YR 5/4, 6/6, and 10YR 7/3 measured), very poorly sorted rounded fU to vcU sands of dominantly quartz in the fine-medium fraction and principally varicolored chert and quartzite with lesser granite in the coarse-very coarse fraction. Gravel are principally massive, but grade upsection into pebbly sands and sands with vague cross-bedding and paleochannel structures. Individual pebble imbrication measurements vary from east-northeast-directed through south-directed; an average of 28 measurements suggests southeastward paleocurrents.

Ancestral Rio San Jose gravel and associated tributary alluvium is poorly exposed throughout Flower Mountain, and in-place outcrop was only identified in one location. In order to provide data constraining the extent of this alluvium, particularly the extent of ancestral Rio San Jose alluvium, the gravel were also mapped where cropping out within landslide blocks, and locations with abundant Rio San Jose gravel at the surface were noted. The distribution suggests that all of Flower Mountain is underlain by ancestral Rio San Jose gravel.

## 3.3. Mount Taylor volcanic field lavas and alluvium

To the south of the Mount Taylor stratovolcano, a basalt-capped plateau extends southward to terminate in a series of flat-topped ridges, three of which jut just across the northern quadrangle boundary onto the Cubero quadrangle. Cretaceous strata underlying and preserved from erosion by the capping basalt flows are discussed later; here the basalts themselves as well as locally-preserved pre-basalt alluvium are described. Lipman et al. (1979), Osburn et al. (2009), and Goff et al. (2015) mapped the volcanics of the Mount Taylor area, with Goff et al. presenting several new $^{40}Ar/^{39}Ar$ dates for the ages of various basalt flows ranging from 1.26 to 3.64 Ma. Two ages were collected from flows to the south of Mount Taylor that could conceivable extend onto the Cubero quadrangle, one of 2.22 ± 0.06 Ma and another, further away, of 2.75 ± 0.03 Ma. Both belong to a generalized "Basalt and trachybasalt, undivided" map unit, precluding certain correlation of these dates to any of the basalt flows described below, but we suggest based on air photo- and ground-based reconnaissance observations that the younger date above belongs to the uppermost flow described below (Qbp).

*Plagioclase-porphyry basalt (Qbp)*

Capping a sequence of four flows (**FIGURE 3.3-1**) on the middle ridge is a medium to dark gray (weathering light to dark brownish gray) massive to weakly flow-foliated plagioclase-phyric basalt. Plagioclase lathes up to 10 mm long (but mainly <1-1 mm long) are 1-2% of fresh faces, subhedral to euhedral, and define the flow foliation. No other phenocrysts are apparent. The groundmass is granular under a hand lens, with very fine vitreous pale gray and black grains that may be plagioclase and pyroxene. The solid core of the basalt is up to 5 m thick, with an additional ~2 m of flow breccia above; the basal contact is unexposed, concealed beneath a ~7 m long stretch of covered slope. The flow rapidly thins southward along the ridge to a pinch out.

*Fine-grained basalt (QTbf)*

The most extensive basalt, apparent in all three ridges, is a dark gray (weathering dark brownish gray) fine-grained flow with sparse (<1%) phenocrysts of vitreous black to dark greenish gray, variably degraded subhedral pyroxene <1 mm across, and very sparse (<<1%) plagioclase phenocrysts up to 2 mm across. The groundmass has a granular texture under a hand lens but individual minerals cannot be identified. The solid core of the flow is locally strongly flow foliated, with vesicles apparent throughout and locally filled with white chalky amygdules. The solid core of the flow is up to about 17 m thick, with unexposed upper and lower contacts. The flow is thickest in the middle ridge and much thinner on both the eastern and western ridges (compare **FIGURES 3.3-1 AND 3.3-2**).

*Porphyritic basalts in paleocanyons (Tbp, Tbp1, Tbp2)*

Along the western flank of the middle ridge, two discontinuous basalt flows crop out beneath the extensive fine-grained flow, apparently filling a paleocanyon (**FIGURES 3.3-1 AND 3.3-3**). The flows are mineralogically and texturally similar and are only mapped individually where both are present and separated by a flow break; in the western ridge, where a signal flow crops out beneath the fine-grained QTbf flow, an undivided map unit is used. Both flows are medium gray (weathering to black) pyroxene-plagioclase porphyries, with phenocrysts occupying 10-15% of fresh faces. Pyroxene is variably degraded vitreous black to dark reddish brown or dark green and anhedral, while plagioclase is typically vitreous white to clear and subhedral. In the upper flow (Tbp2), phenocrysts are up to 5 mm across and pyroxene dominates by up to 2:1; in the lower flow, phenocrysts are up to 1 mm across and pyroxene and plagioclase are subequal. Both flows are up to 6 m thick, but thin rapidly along paleochannel walls to pinchouts. Included in the Tbp2 map unit are very local exposures of light brown, punky-weathered lithic-rich tuff. Lithics are principally 1 to 8 mm across (with sparse outsized clasts up to 20 cm across) of dominantly vesicular basaltic material with sparse quartzose sandstones.

*Alluvium underlying high-level mesas (Tpal)*

Very locally, a matrix-rich, basalt boulder conglomerate crops out beneath Tbp1 along the western flank of the middle ridge (**FIGURE 3.3-4**). The basalt clasts are rounded and consist principally of coarse plagioclase ± pyroxene porphyries with abundant phenocrysts 5 to 20 mm across (**FIGURE 3.3-5**), distinctly different from the basalt flows that overlie the alluvium. Subordinate greenish-gray pyroxene porphyries with much finer phenocrysts and sparse quartzose sandstones and mudrocks are also present. Gravel are poorly sorted, with a max diameter of ~60 cm. The matrix is pink to reddish yellow (5YR 6/6 measured) poorly sorted muddy vfL to fU sands; identifiable grains are mainly quartz with common (~25%)

plagioclase, lesser (~10%) black lithics (basalts?), and rare potassium feldspar (~3-5%). The conglomerate is capped by ~50 cm of weakly planar bedded sands that are similar to the matrix description, with very local milky white carbonate aggregates/nodules and sparse pebbly channel fills. Partially stripped soil has clay films and carbonate coatings on clasts. Exposed thickness of alluvium is 2 m.

## 3.4. Intrusive rocks

Dikes are found throughout the mapped area, mostly with north-south and northwest-southeast orientations. In general, northwest-southeast dikes are plagioclase ± pyroxene porphyries, while north-south dikes are non-porphyritic. The exception is the Acomita dike, which is dominantly fine-grained but northwest-southeast striking. These three categories of dikes are mapped and discussed separately.

*Aphanitic (north-south) dikes (QTbad)*

In the eastern half of the study area, several dominantly north-south oriented dikes intrude Mesozoic strata with mainly fine-grained textures. Dikes are dark gray to brownish gray fresh color with local greenish tints, weathering to black, grayish brown, or brown with variable degrees of reddish to orangish oxide staining. Dike matrices are fine-grained but granular under a hand lens, with a mix of light and dark grains that locally appear prismatic with 90° cleavages, suggesting a plagioclase-pyroxene composition. Dark crystals are locally weathered to dark reddish brown material. Dike cores are only slightly coarser than walls, and no phenocrysts were observed. Sparse xenoliths of wall rock material occur near dike margins. Dikes are up to 1.5 m wide. No geochemical or geochronologic data was recovered for these dikes, and they may be related to the Acomita dike or to later volcanism such as the Plio-Pleistocene activity in the Mount Taylor volcanic field. However, the north-south orientation of these dikes suggests emplacement during late Miocene-Holocene east-west extension as proposed by Aldrich et al. (1986), or emplacement radial to the Mount Taylor volcanic field.

*Porphyritic (northwest-southeast) dikes (QTbpd)*

In the vicinity of the Acomita dike are a number of shorter, subparallel dikes. These dikes are typically more porphyritic than the Acomita dike, with up to 15% phenocrysts of mainly plagioclase with up to a few percent pyroxene. Plagioclase phenocrysts are subhedral to euhedral, white, milky to chalky, tabular, and up to 1 mm across. Pyroxene phenocrysts are anhedral with black glassy cores and reddish brown rims, and up to 1 mm across. Dike matrices are medium gray weathering to brownish gray with variable oxide staining. Dikes are up to 1.5 m wide. No geochemical or geochronologic data was recovered for these dikes, and they may be related to the Acomita dike or to later volcanism such as Plio-Pleistocene activity in the Mount Taylor volcanic field. However, their northwest-southeast orientation suggests emplacement during late Oligocene-early Miocene northeast-southwest extension as proposed by Aldrich et al. (1986).

*Acomita Dike (Tbda)*

The Acomita dike of Laughlin et al. (1983) is a north-northeast trending basaltic andesite dike that is exposed over approximately 10 km. On the Cubero quadrangle it is generally weakly porphyritic with 0-2% phenocrysts of mainly plagioclase with sparse pyroxene. Plagioclase is mainly subhedral, white, vitreous, and up to 1 mm across. Very locally, megacrysts (or xenocrysts or crystal aggregates) of plagioclase up to 1 cm across that are anhedral, oblate, and rounded are found. Pyroxene is subhedral to anhedral, black, vitreous, and up to 1 mm across. The matrix of the basalt is finely granular, but minerals cannot be identified. Color is dark gray, weathering to dark grayish brown with variable degrees of reddish, brownish, and black oxide staining. The dike is generally poorly exposed, and has a pervasive, densely spaced subvertical flow foliation fabric and/or fracturing. Sparse sandstone xenoliths up to 0.5 cm across can be found along dike margins. The dike is generally 0-4 m wide, but can be as wide as 10 m. Laughlin et al. report a K-Ar age of 30.7 ± 1.4 Ma for the dike.

The flow foliation fabric is very locally tightly folded, with the hinge line trending 75° to S25W. Although the exact shape of the fold was not clear and the exact sense of shear that formed the fold unknown, the steep plunge of the fold axis would suggest that shearing occurred in a subhorizontal plane, which would suggest subhorizontal flow and dike propagation. The direction of propagation is not constrained.

## 3.5. Cretaceous System

### 3.5.1. Mancos Shale (Km)

The Mancos Shale, originally of Cross and Purington (1899), has been progressively expanded from its type locality by Mancos, Colorado, throughout most of the western United States (cf., Leckie et al., 1997). Several members and tongues of the Mancos have been proposed, many of which are defined by laterally-restricted features such as intercalated sandstone intervals. As a result, the nomenclature of the Mancos changes substantially across its extent. The nomenclature used here is derived principally from Hunt (1936), Maxwell (1982, 1990), Hook et al. (1983), and Landis et al. (1973).

In general, the Mancos is very poorly exposed and as a result the following descriptions are highly generalized. Due to poor exposure, the member-rank unit cannot always be determined for every region of shale; in these cases, an undivided "Km" map unit is used.

#### *Mulatto Shale Tongue (Kmm)*

The Mulatto Shale Tongue of Hunt (1936) was defined as the sequence of marine shales lying between the Dilco (Coal) and Dalton Sandstone Members of the then-Mesaverde Formation (which was later raised to Group rank, with the Dilco and Dalton subsumed into the Crevasse Canyon Formation by Allen and Balk, 1954). On this quadrangle, however, the Borrego Pass Lentil (a.k.a. the "stray sandstone") lies between the Dilco Member and the marine shales of the Mulatto, and the top of the Tongue is not preserved as the unit has been truncated by an angular unconformity. The Mulatto consists of dark gray to tan, thinly laminated, very poorly exposed shales. The preserved thickness is 0 to about 28 m thick.

#### *Gallup-intercalated tongues (Kmg1, Kmg2)*

Two poorly-exposed and unnamed tongues of the Mancos Shale intercalate with tongues of the Gallup Sandstone on the Cubero quadrangle. Both consist of thinly laminated dark gray to grayish brown (10YR 4/1 and 2.5Y 5/2 measured) gypsiferous shales and locally sandy shales. The upper section (Kmg2) also includes at least one interval of pale brown (2.5Y 8/3 measured) muddy fine sandstones consisting of poorly sorted vfL to fL grains of quartz, sparse feldspars (<1-1%), and sparse black lithics (<1%). Sandstone beds are up to 3 cm thick. The lower tongue (Kmg1) is about 12 to 16 m thick, while the upper tongue (Kmg2) is about 15 to 20 m thick.

#### *Upper "main body" (Kmu)*

The "main body" of the Mancos Shale, a term originally used by Hunt (1936) and continued by USGS mappers (cf., Maxwell, 1982, 1990), is used in this area for the sequence of shales lying between the uppermost Dakota Sandstone tongue (Twowells Sandstone Tongue) and lowermost Gallup Sandstone body (in this case, the "F" Tongue). Implicit in this definition is that the Tres Hermanos Formation is not present; to the south and west, the sandstones of the Tres Hermanos divides the "main body" into the lower Rio Salado and upper Pescado (or D-Cross, where the "F" Tongue of the Gallup is missing) Tongues

(Hook et al., 1983). In this report, the "main body" is divided into upper (Kmu) and lower (Kml) sections by the Bridge Creek Limestone Member. This is done because the limy shales of the Bridge Creek can often be identified in colluvium (see below), which allows the two to be separated across the map area. The Semilla Sandstone Member, which is only locally distinguishable, is included within the upper "main body."

Small exposures of the upper "main body" are mostly light to dark gray but locally brownish gray (2.5Y 5/1, 5/3, and 6/3 measured), commonly gypsiferous, and very finely laminated (laminae commonly <0.1 mm thick). Shales, particularly more brown-colored shales, are locally sandy with up to 2% vfL sand-sized grains. Shell fragments and imprints are sparse overall, but locally abundant (**FIGURE 3.5-1**). Beds of tan very fine sandstone and crystalline gypsum are sparse, but up to 30 cm thick where found. The upper "main body" unit as used here is approximately 125 m thick according to cross-section reconstructions.

*Uppermost Semilla Sandstone Member (Kms)*

The Semilla Sandstone Member of the Mancos was defined by Dane et al. (1968) and formally extended into the Cubero quadrangle by Fleming (1989) with a 25 m-thick reference section in San Jose Canyon consisting of two intervals of sandstones and silty sandstones separated by 7.5 m of covered material interpreted to be shale. Due to abundant landslides in the area, the interval and adjacent Mancos Shales are particularly poorly exposed on the quadrangle, with Fleming (1989) stating the interval "could not be followed east or west away from the San Jose Canyon area." Although the lower sandstone interval is typically covered and indistinguishable from the remainder of the upper "main body" of the Mancos, the upper sandstone interval can often be identified either in outcrop or as a persistent topographic bench. Thus, the top of the Semilla Sandstone Member was mapped, but only as a marker bed, as the remainder of the Semilla could not be consistently identified. Note that this means an unknown thickness of Semilla Sandstone lies beneath the mapped uppermost Semilla Sandstone marker bed.

The uppermost Semilla Sandstone Member sandstone interval is approximately 2 m thick of pale brown (2.5Y 7/3 and 7/4 measured) weathering light orangish brown, wavy-bedded, laminated to thinly bedded (0.5-2 cm thick), moderately to poorly sorted, variably muddy vfL to fL sandstones (**FIGURE 3.5-2**). Beds are moderately well indurated by calcitic cement. Grains are dominantly vitreous and pale gray in color, but could not be identified with surety under a hand lens. The thickness of the full Semilla Sandstone Member on this quadrangle is unknown.

*Lower "main body" (Kml)*

The lower "main body" of the Mancos as used here consists of the Bridge Creek Limestone Member and underlying shales down to the top of the Twowells Sandstone Tongue of the Dakota Sandstone. The Bridge Creek Limestone Member was originally described by Bass (1926) for a sequence of alternating limy shale and thin chalky limestone in Kansas. The unit was formally correlated to limestones in New Mexico based on faunal evidence by Hook and Cobban (1981) and subsequently expanded into west-central New Mexico by Hook et al. (1983). Specific nomenclature and stratigraphic assignment for the unit varies with region; Hook and Cobban (1981) assigned the Bridge Creek as a member to locally both the Colorado Formation and the Mancos Shale, but Hook et al. (1983) reduced the unit in rank to the Bridge Creek Limestone Beds of their newly-defined Rio Salado Tongue of the Mancos Shale. Maxwell (1982, 1990) previously described the Bridge Creek as beds of the Mancos Shale in the Cubero area, but Kirk et al. (1988) assigned the unit member rank further west. We describe the Bridge Creek Limestone as a member for the following reasons: 1) given the absence of the Tres Hermanos

Formation, the Rio Salado Tongue of the Mancos, as defined by Hook et al. (1983), is not present in the area, and therefore their assignment of the Bridge Creek as beds of the Rio Salado does not apply, and 2) within the San Juan basin, of which the Cubero quadrangle is a part, the unit is typically assigned member rank (cf., Fassett, 2010; Kirk et al., 1988; Molenaar and Baird, 1989).

The Bridge Creek Limestone Member is combined with the underlying shales due to the poor exposure of the unit, which generally precludes precisely locating the base of the Bridge Creek. Unlike the overlying Semilla Sandstone Member, the Bridge Creek Limestone can often be identified even in areas of poor exposure due to the unique appearance of the limy shales found within the Bridge Creek. Where these shales are found in abundance in the surface cover, we interpreted the Bridge Creek Limestone Member to lie just below the cover, and mapped the area as the lower "main body" unit.

The lower "main body" of the Mancos Shale consists of interbedded shales, limy shales, and fine-grained carbonate grainstones (calcarenites), typically weathering to a pale yellowish brown color (2.5Y 8/2 and 8/3 measured) that is distinctive to the Mancos section (**Figure 3.5-3**). The fresh color of the limy shales and grainstones is a dark gray (10YR 4/1 measured). Carbonate beds are well indurated and erosion resistant, forming thin (mostly up to 2 cm thick, locally up to 20 cm thick) ledges that weather out from the less resistant shales. Ledges can be internally massive, planar laminated, or cross-laminated, with grains dominantly mud to vfL sand size but locally as coarse as fL sand. Thicker beds, particularly toward the top of the section, contain common carbonate nodules. Slopes underlain by the lower "main body" are often lighter-colored than surrounding Mancos Shale slopes, and are covered with common plates of limy shale. Unit is approximately 21-22 m thick in cross-section reconstructions.

#### *Whitewater Arroyo Shale Tongue (Kmw)*

The Whitewater Arroyo Shale Tongue was named by Owen (1966) for shales underlying the Twowells Sandstone Tongue in the San Juan basin. The name was progressively incorporated into USGS maps in the Grants-Mount Taylor uranium district, and later used by Landis et al. (1973) for the shales lying between the Pagaute (below) and Twowells Sandstone Tongues of the Dakota. This unit is very poorly exposed on this quadrangle, but it generally consists of light to dark gray, well-laminated shales and lesser siltstones. Landis et al. also report lenticular bentonite and limestone concretions. Unit thickness is only locally constrained along the eastern margin of the quadrangle, where it is approximately 28 m thick.

#### *Clay Mesa Shale Tongue (Kmc)*

The Clay Mesa Tongue was named by Landis et al. (1973) for the section of shales between the Cubero (below) and Paguate Sandstone Tongues of the Dakota. This unit is very poorly exposed on this quadrangle, but it generally consists of medium to dark gray, well-laminated shales. Landis et al. also report thin bentonite and limestone beds and limy concretions, as well as a few sandy beds toward the top. Unit thickness is only locally constrained along the eastern margin of the quadrangle, where it is approximately 21 m thick.

#### *Undivided Whitewater Arroyo and Clay Mesa Shales (Kmwc)*

Where the Paguate Sandstone Tongue of the Dakota is absent, the Whitewater Arroyo and Clay Mesa Tongues cannot be distinguished from one another. In these areas, an undivided unit is used to represent the section of shales lying between the Cubero (below) and Twowells Sandstone Tongues. Combined unit thickness is up to 71 m in cross-section reconstructions.

### 3.5.2. Crevasse Canyon Formation (Kc)

The Crevasse Canyon Formation was named by Allen and Balk (1954) for the interval of sedimentary rocks between the Gallup Sandstone and the Point Lookout Sandstone in the Fort Defiance-Tohatchi area, subsuming the pre-existing Gibson (Coal), Dalton Sandstone, and Dilco (Coal) Members. Typical usage excludes tongues of marine shale from the Crevasse Canyon. Only the lower members of the formation are present on this quadrangle, although the upper members can be found further north.

#### *Borrego Pass Lentil (a.k.a. the stray sandstone; Kcb)*

The Borrego Pass Lentil of Correa (1970) is the oft-overlooked formal name for the "stray" sandstone noted but not named by Sears et al. (1941). It is discontinuous through the San Juan basin (cf., Molenaar et al., 1996), but common to the Grants area. On this quadrangle, the unit consists of white to pale gray or pale brown (10YR 8/3 measured), medium to thinly bedded (10-20 cm thick), generally cross-stratified very fine to medium sandstones with local coarse-grained sandstone channel-fills (**Figure 3.5-4**). Most beds are moderately or poorly sorted vfU to mL sands of dominantly quartz with up to 10% tabular feldspars, up to 5% chalky or milky white chert(?) lithics, and sparse (<1%) black lithics. Channel-fills are poorly sorted fU to cU grains of similar composition, with additional very sparse (<<1%) chalky white rounded siliceous (chert?) pebbles up to 1 cm in diameter; fills are up to 5 cm thick and lenticular. Beds are variably stained pale orangish brown by oxides. The lower contact is unexposed on this quadrangle, but reportedly gradational to the north (Goff et al., 2008). The upper contact is an angular unconformity. Preserved thickness is 0 to about 20 m.

#### *Dilco Member (Kcdi)*

Originally named by Sears (1925), subsequently assigned to the Crevasse Canyon Formation as the Dilco Coal Member by Allen and Balk (1954), and much later redefined as the Dilco Member by Nummedal and Molenaar (1995) to reflect the regional relative scarcity of coal in the unit. The unit is very poorly exposed on this quadrangle, but consists of interbedded siltstones, sandstones, and shales that are very locally coal-bearing. Siltstones and shales are gray to light brown with local reddish or pinkish hues (e.g., 2.5YR 7/3 and 5YR 5/2 measured) or dark gray to black where carbonaceous; both are thinly planar laminated and generally unexposed. Sandstone intervals are more prominent, cropping out in 1 to 1.5 m thick sections of pale brown to pale gray (10YR 8/3 and 2.5Y 8.5/1 measured), thin to medium bedded (2-20 cm thick), moderately or poorly sorted vfL to fL sandstones (**Figure 3.5-5**). Beds are planar to wedge-shaped, massive to internally cross-laminated, and locally bear bedding-perpendicular hollow casts that may be root casts (**Figure 3.5-6**) as well as small pits that may be raindrop imprints on some bedding surfaces. Sand grains are quartz-dominated with only a few percent tabular feldspars, milky light brown chert(?) lithics, and black lithics. Some sandstone intervals bear reddish brown concretions. The lower contact is unexposed on this quadrangle, but reportedly gradational to the north (Goff et al., 2008). Preserved thickness about 45 to 50 m.

### 3.5.3. Gallup Sandstone (Kg)

Sears (1925) originally utilized the term Gallup for a sequence of three sandstone beds interbedded with shales and coals in northwestern New Mexico. Molenaar (1983) later designated a type section that extended down to include a fourth sandstone interval. Measured sections and well log studies from throughout the San Juan basin (most recently summarized by Molenaar et al., 1996) further established the stratigraphy of the Gallup sequence and subdivided the unit regionally into six sandstone intervals, designated A through F. Here, the sandstone bodies intercalate with shales of the Mancos, and can be fairly described as "tongues." The designations C, E, and F are after the regional studies summarized by Molenaar et al. (1996).

### *"C" tongue (Kgc)*

The "C" tongue of the Gallup is about 25 to 28 m of weakly coarsening-upwards quartz sandstones. Sandstones at the base consist of moderately-poorly sorted muddy vfL to fU sands in tabular, wedge-shaped, or broadly lenticular, commonly cross-stratified beds up to ~20 cm thick. Sandstones in the middle section are moderately sorted vfL to fL sandstones in planar tabular beds ~10-30 cm thick. At the top, sandstones consist of moderately sorted fL to fU sands again in tabular beds, here locally massive and up to ~60 cm thick, with bedding-parallel burrow structures suggesting the lack of structure is a result of bioturbation. Throughout, sandstones are pale yellow to pale brown (5Y 8/3, 2.5Y 8.5/2, and 2.5Y8/4 measured) and consist dominantly of subrounded to rounded grains of quartz with up to 4% tabular feldspars, up to 1% black lithics, and sparse chalky white chert(?) lithics. Basal contact is gradational with underlying shales.

The "C" tongue of the Gallup (after Molenaar et al., 1996) is referred to as the "main body of the Gallup" in previous reports (e.g., Maxwell, 1982, 1990). The "C tongue" designation is used here for its regional significance.

### *"E" tongue (Kge)*

The "E" tongue of the Gallup consists of an approximately 7 to 14 m thick sequence of coarsening-upwards sandstones that additionally become better structured upsection (**Figure 3.5-7**). The basal 1 m of the unit consists of planar-laminated vfL-vfU sandstones that are gradational with the underlying shales. Above the basal 1 m, sandstones are principally massive or weakly bedded, with thin backfilled burrows (**Figure 3.5-8**) suggesting that bioturbation is responsible for the weak structure. Massive beds are up to about 2 m thick, while structured beds are up to 30 cm thick and locally cross-bedded. Sands are moderately sorted vfL to vfU. Higher in the section, massive beds become rare, and tabular to wedge-shaped, common cross-stratified beds up to ~20 cm thick dominate. The top 1 m of the section is distinctly light brown-weathering (**Figure 3.5-9**), with sands consisting of moderately sorted fL to fU grains. Throughout, fresh color is pale gray to pale brown (2.5Y 8/1-8/2 to 10YR 8/1 measured), cement is calcitic, and grains consist dominantly of quartz with up to 5% tabular feldspars, up to 5% black lithics, and <1-1% milky light brown chert(?) grains.

The "E" tongue of the Gallup (after Molenaar et al., 1996) is referred to as the "upper tongue of the Gallup" in previous reports (e.g., Maxwell, 1982, 1990). The "E tongue" designation is used here for its regional significance.

### *"F" tongue (Kgf)*

Unlike the higher tongues of the Gallup, the "F" tongue consists of two sandstone sequences separated by an unnamed shale interval (**Figure 3.5-10**). Both sequences are coarsening-upwards sequences that are gradational with underlying shale strata, grading from shale through thin (<10 cm thick) planar tabular beds of vfL to fL sandstones to medium (20-30 cm thick) wedge-shaped cross-stratified beds of fL to mL sandstone. Tabular beds are variably massive or internally planar laminated and very locally cross-stratified, with very sparse shell fragments and imprints. Bedding-perpendicular and bedding-parallel backfilled burrows are locally found in cross-stratified sandstones, as are discontinuous shale lenses. Throughout, sandstones are very pale brown (10YR 8/1 to 8/4 measured), weathering to a brownish yellow (as strong as 10YR 6/6), and composed of moderately sorted and rounded sand grains of dominantly quartz, up to 5% tabular feldspars, up to 1% milky brown chert(?) lithics, and sparse (<1%) black lithics. Cement is calcitic. The lower sandstone sequence is approximately 5 to 6 m thick, while the upper sequence is approximately 13 to 16 m thick. The intervening shale interval, which consists of poorly exposed gray to light brownish gray (2.5Y 5/1 to 10YR 6/2 measured) gypsiferous finely laminated shales, is approximately 2-3 m thick. Shales are variably sandy, with up to 15% vfL grains of quartz being found in some layers. The basal contact of the shale interval is sharp with the underlying lower sandstone sequence.

The top of the "F" tongue is marked by a distinctly brown-weathering, well-indurated, and strongly bedded sandstone interval. Beds are wavy planar parallel, thin (up to 10 cm thick), and typically cross-stratified, with moderately sorted fL to mU grains. Sand grain and cement composition is similar to underlying sandstones.

The "F" tongue of the Gallup (after Molenaar et al., 1996) is referred to as the "lower tongue of the Gallup" in previous reports (e.g., Maxwell, 1982, 1990). The "F tongue" designation is used here for its regional significance.

### 3.5.4. Dakota Sandstone (Kd)

The Dakota Sandstone is an extensive interval of clastic sedimentary rocks originally named by Meek and Hayden (1862) for exposures in Nebraska. The term has been variably expanded and restricted through the decades, but its use is firmly established in the San Juan basin. Notable papers concerning the local Dakota stratigraphy include Pike (1947), Owen (1966), and particularly Landis et al. (1973). A recent summary of the stratigraphy for this area was published by Owen and Owen (2003). Nomenclature used here is in keeping with these previous studies with the addition of the Encinal Canyon Member of Aubrey (1988).

#### *Twowells Sandstone Tongue (Kdt, Kdtb)*

The Twowells Sandstone Tongue of Pike (1947) is a laterally extensive sandstone interval that occurs over much of the southern and southeastern San Juan basin (Landis et al., 1973; Maxwell, 1982; Owen and Owen, 2003). Despite this regional extent, however, outcrop of the Twowells within this quadrangle is limited. Two sets of sandstone outcrop within the quadrangle are assigned to the Twowells, one along the eastern margin of the quadrangle, where sandstones can be followed eastward onto the Laguna quadrangle and into the Dakota-Mancos reference section measured by Landis et al. (1973), and another to the northwest of Flower Mountain, where the stratigraphic assignment is based on the stratigraphic location of the outcrop directly below the Kml map unit. Maxwell (1982, 1990) interpreted this outcrop pattern to indicate that the sandstone body pinches out and is not present in the subsurface through the exposed stretches. However, we note that between the two areas of Twowells outcrop there is a discontinuous topographic bench that occurs coincident with the base of the Kml map unit, which we interpret to be the surface expression of a poorly exposed and likely thinned and/or finer-grained interval that is correlative to the Twowells Sandstone Tongue, which we map as "Kdtb." If this interpretation is correct, then the Twowells Tongue is more extensive than inferred by Maxwell, although the region of no outcrop in the west half of the quadrangle may still reflect absence of the Twowells Sandstone unit.

Exposures along the eastern margin of the quadrangle reveal an approximately 12 m thick sequence of generally coarsening-upwards sandstones that grade from the underlying shales of the Westwater Arroyo Shale Tongue through a sequence of poorly sorted muddy vfL to vfU sandstones upwards to clean moderately sorted vfU to fU sandstones (FIGURE 3.5-11). Beds are typically thin (0-20 cm thick) in the lower 4 m, medium (0-50 cm thick) in the center, but thin again (0-10 cm thick) in the top 2 m. Except for the top 2 m, beds are mainly wavy planar parallel or wedge-shaped and massive to indistinctly cross-stratified; the top 2 m are generally wedge-shaped and cross-stratified. Throughout, sandstones are pale yellowish or brownish gray (2.5Y 7/3 to 7/4 and 10YR 7/4 to 8/3 and 8/4 measured) and consist of rounded grains of dominantly quartz w up to 10% chalky pale brown chert(?) lithics, <1-1% tabular feldpsars, and <1% black lithics. Bedding-parallel backfilled burrows are common to the tops of some beds. Exposures of the Twowells Sandstone northwest of Flower Mountain show that the top of the Tongue can be locally coarser, as here it is a well sorted fU to mL, cross-stratified sandstone.

### *Paguate Sandstone Tongue (Kdp, Kdpb)*

The Paguate Sandstone Tongue of Landis et al. (1973) crops out only along the western and eastern margins of the quadrangle. Measured sections by Landis et al. (1973) and Owen and Owen (2003) and regional observations by Maxwell (1982, 1990) indicate the thickness of the Paguate varies considerably more across the southeastern San Juan basin as compared to the Cubero and Twowells Tongues and is locally absent. Thus, the lack of outcrop through the central portion of the quadrangle likely reflects the absence of the unit in this area (Maxwell, 1982, 1990). Southeast of the town of Cubero along the eastern edge of the quadrangle, a topographic bench, mapped as "Kdpb," is found at a comparable elevation to nearby outcrop of sandstone, which is interpreted to be underlain by Paguate sandstones or siltstones. Unlike with the Twowells Sandstone Tongue, this topographic bench is not extensive and cannot be followed across the quadrangle.

Good exposures of the Paguate Sandstone immediately east of the study area on the Laguna quadrangle reveal the Tongue consists of a coarsening-upwards sequence of laminated pale brown siltstones grading to moderately well sorted fU to mL sandstones at the top. Beds, thin to medium (10-50 cm thick) throughout, grade from commonly massive and wavy-planar to wedge-shaped and cross-bedded upsection as well (FIGURE 3.5-12). Throughout, sandstones are typically pale brown to yellow in color (2.5Y 7/4 to 8/6) and consist of rounded sand grains of dominantly quartz with up to 5% tabular feldspars, up to 5% milky pale brown to light gray chert(?) lithics, and <1% black lithics. Cement is calcitic, and beds commonly display a knobby weathering texture. Locally, surfaces have weathered to a dark brown patina. The basal contact with the underlying Clay Mesa Shale Tongue is gradational. The thickness of the unit is poorly constrained within the quadrangle boundaries, but is estimated to be 0 to 10 m thick.

### *Cubero Sandstone Tongue (Kdc)*

The Cubero Sandstone Tongue of Landis et al. (1973) is a generally thick and laterally continuous horizon in the Dakota-Mancos sequence (cf., Owen and Owen, 2003). On this quadrangle, the section is approximately 9-11 m thick and consists of two distinct coarsening-upwards sequences (FIGURE 3.5-13). The lower sequence, 7-8 m thick, is gradational with the underlying shales of the upper Oak Canyon Member, and grades from moderately poorly sorted vfL to fL quartz sandstone in thin to medium beds (5-50 cm thick) at the base to well sorted fL to fU quartz sandstone in beds up to 1 m thick at the top. Lower beds are commonly planar tabular to locally wedge-shaped and internally massive or planar laminated and only locally cross-stratified, while upper beds are commonly wedge-shaped and typically internally cross-stratified with local massive structure. The abundance of burrows, both bedding-parallel and bedding-perpendicular, increases upsection as well, though remains rare even in uppermost beds. Throughout, beds are pale gray to very pale brown (2.5Y 8/2 to 9/2 and 7.5YR 4/6 measured), moderately to moderately-well indurated by calcitic cement, and composed dominantly of quartz with up to 5% tabular feldspars, <1-2% chalky white lithics (cherts?), and <1% black lithics.

The upper coarsening-upwards sequence is separated from the lower by a sharp decrease in erosion resistance marked by a commonly prominent ledge formed by the top of the lower sequence. The upper sequence is approximately 2-3 m thick, and consists of laminated siltstones at the base grading upsection to moderately sorted vfL to fL sandstones. Sandstone beds are typically thin to medium (10-20 cm thick) and wedge-shaped with internal cross-stratification. Bedding-parallel burrows are common to the tops of sandstone beds. Colors and sand grain compositions are similar to the lower sequence.

*Oak Canyon Member (Kdou, Kdol)*

The Oak Canyon Member of Landis et al. (1973) is commonly divided into an upper shale-dominated subunit (Kdou) and a lower subunit of interbedded sandstones and shales (Kdol). On this quadrangle, the lower subunit consists of two sandstone intervals separated by a poorly-exposed medial shale interval. The lower sandstone interval, which is approximately 9-12 m thick, is typically pale gray in color (2.5Y 8/1 measured) and composed of well sorted fL to mL sands, rounded, dominantly quartz with <1-2% tabular feldspar crystals and <1% black lithics. Beds are typically planar tabular to planar wedge-shaped, with local lenticular beds, and thicken from 10-15 cm thick at the base to upwards of 60 cm thick toward the top. Internally, beds are commonly cross-stratified and less commonly massive (**Figure 3.5-14**); locally, bedding-perpendicular backfilled burrows are apparent. From approximately 2 to 3 m from the top of the lower sandstone interval, there is a distinctly well-indurated (with a calcitic cement) and dark brown-weathering section (**Figure 3.5-15**) that is somewhat finer-grained (fL-fU sands) and bears more abundant lenticular beds with cross-stratification. The fresh color of this interval is still pale (5YR 8/3 pink measured), and the sand composition remains the same and before. The basal contact of the lower sandstone interval is gradational with the underlying Encinal Canyon Member.

The medial shales interval is approximately 6-8 m thick of thinly laminated gray to locally pale yellowish brown (2.5Y 5/1 to 7/1 and 2.5Y 8/4 measured) shales. Sparse pockets of vfL sand grains can be found. The basal contact of the shale is sharp with the underlying lower sandstone interval; the shale grades upsection into the overlying upper sandstone interval over a ~1 m thick section of siltstones and white, finely planar laminated, fine-grained sandstones. The bulk of the upper sandstone interval (**Figure 3.5-16**), which is approximately 1.5-2 m thick, is pale brown (10YR 8/3 measured), thinly bedded (2-20 cm thick), massive to cross-stratified and composed of moderately well sorted vfL to fU sands, rounded, dominantly quartz with up to 3% tabular feldspars and <1% light gray to black lithics. This interval is marked by a common knobby weathering texture, and bedding-parallel backfilled burrows are locally abundant at the tops of some beds.

The upper Oak Canyon Member is approximately 10 to 12 m thick of poorly exposed gray (10YR 6/1 to 5/1 measured) shales with local yellowish brown discoloration (10YR 7/6 measured; **Figure 3.5-17**). Shales are thinly laminated and fissile. The lower contact with the lower Oak Canyon is sharp.

*Encinal Canyon Member (Kdec)*

The Encinal Canyon Member of Aubrey (1988) is a thin fluvial conglomeratic sandstone unit common to the base of the Dakota Sandstone along the eastern flank of the San Juan basin. On this quadrangle, it consists of 2 to 10 m of pale gray (5YR 7/1 and 10YR 8/1 to 9/1 measured) sandstones, pebbly sandstones, and pebble conglomerates in thin to medium (0-50 cm) lenticular cross-stratified beds (**Figure 3.5-18**). Sandstones dominate, and are most commonly composed of poorly sorted vfU to mU sand grains of rounded quartz, 1-2% feldspar, and <1% dark gray lithics. Pebbly sandstones are ~20% of outcrop, and composed of poorly sorted pebbles up to 2 cm diameter supported by a vfU to vfU sand matrix. Gravel are dominantly rounded medium to dark gray cherts and quartzite with lesser angular to rounded chalky white cherts and sparse rounded granites (**Figure 3.5-19**). Chalky white cherts become increasing more abundant upsection, and dominate the coarser sand sizes in upper beds. Pebble conglomerates are ~5% of outcrop and compositionally similar to the pebbly sandstones. Yellowish brown redox bands (as strong as 10YR 6/6 coloration) are common throughout, and very locally yellowish brown iron oxide concretions occur along preferred bedding plans.

## 3.6. Jurassic System

### 3.6.1. Brief discussion of disagreements surrounding Jurassic stratigraphic nomenclature of northwestern New Mexico

Disagreement is nothing new or unusual in stratigraphy, and disputes can prolong for decades without resolution. One such pervasive dispute exists regarding the Jurassic System of northwestern New Mexico, generally waged between the proposals of Condon and Huffman (1988) and Anderson and Lucas (1992). Much of the dispute revolves around the interpretations of measured sections from southeastern Utah, well outside the scope of this project. In the interest of providing enough background for correlating the map units used here to a regional framework, as well as to previous studies, I (Cikoski) provide my best understanding of the argument with respect to the units cropping out on this quadrangle, complete with justification for the stratigraphy used herein. Although these two proposed stratigraphies disagree at several levels, the only dispute of interest to this report is the section of eolian and interbedded eolian and fluvial strata occurring above the Todilto Limestone and below the Morrison Formation. This report refers to these strata as the main facies of the Zuni Sandstone and the fluvial facies of the Zuni Sandstone; a brief discussion of each is given below.

The main facies of the Zuni Sandstone as used here consists of a suite of yellowish, distinctly eolian cross-stratified sandstone in the Jurassic System beneath the Morrison Formation and above the Todilto Limestone. This section has been recognized in many geologic maps of the Grants-Mt Taylor uranium mining district, but multiple names were given for the interval. Some correlated the interval to the Bluff Sandstone of Baker et al. (1936), imported from Utah (e.g., Moench, 1963, 1964); others to the Zuni Sandstone of Dutton (1885) from the area of Zuni, New Mexico, to the west (e.g., Maxwell, 1986, 1990); still others to the Cow Springs Sandstone of Harshbarger et al. (1957) from Arizona (e.g., Green and Pierson, 1971); and finally some skirted the issue by just calling it the “yellow sandstone” (e.g., Thaden et al., 1967). In addition, Condon and Peterson (1986) would later call some of these sandstones the “sandstone at Mesita,” before assigning them to the “eolian facies of the Recapture” (Condon, 1989). Fortunately, the list of names proposed for the prominently cross-bedded sandstones has subsequently dwindled, and neither the Condon and Huffman (1988 [as modified by Condon, 1989]) nor Anderson and Lucas (1992) schemes recommend the use of the terms “Bluff Sandstone,” “Cow Springs Sandstone,” “sandstone at Mesita,” or “yellow sandstone” for these strata anymore.

The main facies of the Zuni Sandstone is overlain by a sequence of fluvial sandstones, eolian sandstones, and rare mudstones that is here referred to as the fluvial facies of the Zuni Sandstone. Previous studies have variably included this section with the Zuni Sandstone as a “fossil soil zone” (Maxwell, 1990); interpreted the section as the Recapture Member of the Morrison Formation (e.g., Condon, 1989; Moench, 1963); or interpreted the section to be a Recapture Member of the Bluff

Sandstone (Anderson and Lucas, 1995, 1996; note that Anderson and Lucas' definition of the Bluff Sandstone differs from that of some previous workers, e.g. Condon and Huffman, 1988). Crucially, these previous authors agree that the sequence from the main facies through the fluvial facies (*sensu* this report) is conformable, and based on our observations on this quadrangle we similarly interpret a conformable sequence, as the interbedded fluvial and eolian sandstones are compositionally very similar to the underlying eolian sandstones, and no erosive or significant non-depositional break in the sequence is apparent.

The nature of the upper contact of this sequence is debated, however. Maxwell (1990) and Anderson and Lucas (1995, 1996) explicitly state the upper contact is unconformable, while Condon (1989) implicitly interprets a conformable upper contact, as indicated by his inclusion of the Zuni Sandstone (*sensu* this report) with the Morrison Formation. Our observations on this quadrangle would suggest the upper contact is unconformable: 1) the uppermost sandstones of the interbedded fluvial/eolian sequence are enriched in fines and have local carbonate nodules, which could be a product of soil development; 2) a substantial change in depositional style appears to occur at the contact, with interbedded fluvial and eolian sediments below, but only fluvial or lacustrine sediments above; 3) the contact marks a sharp change in grain size, with fine-grained sandstones below and pebbly coarse-grained sandstones above; and 4) the contact is wavy and marginally scoured. We therefore agree with Maxwell (1990) and Anderson and Lucas (1995, 1996) that an unconformity separates the two facies of the Zuni Sandstone (*sensu* this report) from the overlying Morrison Formation.

Given the presence of an unconformity in the sequence, we reject the proposal of Condon (1989) to assign the Zuni Sandstone (*sensu* this report) to the Recapture Member of the Morrison Formation (*sensu* Condon, 1989). We also reject the interpretation of Maxwell (1990) that the fluvial facies of the Zuni Sandstone (*sensu* this report) is a "fossil soil zone," as the preserved fluvial structures in this unit, as well as the presence of sparse pebbles, would suggest the sequence is the product of some amount of fluvial deposition and/or reworking, and not the product solely of soil development. We also choose not to use the term "Recapture Member of the Bluff Sandstone" of Anderson and Lucas (1995, 1996); both the Recapture and the Bluff are units defined in Utah, far removed from this study area, with which the authors have only limited experience, and we are reluctant to accept redefinitions of these terms without more concurrence from the geologic community.

Given these considerations, we have chosen to map the eolian and fluvial sandstones and rare mudstones overlying the Todilto Limestone and underlying the Morrison Formation as main and fluvial facies of the Zuni Sandstone. This is in keeping with the revised definition of the Zuni Sandstone presented by Anderson (1993), a restriction of the term as originally proposed by Dutton (1885).

### 3.6.2. Morrison Formation (Jm)

#### *Brushy Basin Member (Jm)*

The bulk of the Morrison Formation on this quadrangle consists of poorly exposed mudstones, rare sandstones, and sparse conglomerates of the Brushy Basin Member. Mudstones are varicolored, ranging from light reddish brown to pink to greenish gray (7.5R 5/2, 2.5YR 5/3, and 5GY 7/1 measured; **Figure 3.6-1**), with common clayey weathering textures and very stiff consistencies when struck with a hammer. Sedimentary structures are difficult to ascertain, but mudstones typically break into very thin plates, suggesting a common thin planar lamination. Sparse (<1%) very fine sand grains of quartz and lesser feldspar are locally present, as are very fine (<0.1 mm diameter), rounded, white, chalky carbonate nodules.

Sandstones in the Brushy Basin are typically pale gray or yellowish in color (2.5Y 9.5/1 and 5Y 7/3 measured), with local yellowish red colors (5YR 4/6 measured). Exposures are poor but suggest sandstone bodies are discontinuous and lenticular in shape, and composed of thin to thick (0-1.2 m thick) cross-bedded lenticular beds of poorly to moderately sorted, variably muddy, vfL to mU sands, rounded, of mainly quartz with up 10% feldspars, up to 10% brown to light gray cherts, and sparse black lithics. Beds are poorly to moderately well indurated, and locally grade upsection into pale greenish gray mudstones.

Sparse conglomerate beds are pale gray (10YR 9/1 measured), lenticular, indistinctly cross-bedded, and up to 30 cm thick (**Figure 3.6-2**). Pebbles are up to 2 cm diameter, moderately to poorly sorted, clast-supported, subrounded to rounded, and composed of common varicolored chert and quartzite and sparse granite and white chalky chert. The conglomerate matrix is mainly poorly sorted mL to vcL sands grains, rounded, of dominantly quartz with up to 20% quartzite, up to 10% chert, and <1-2% feldspars. Exposed thickness of 60 to 95 m. Well log interpretations presented by Lupe (1983) suggest the unit thickens northward.

*Westwater Canyon Member (Included with Jm)*

Between the sandstones and rare mudstones of the fluvial facies of the Zuni Sandstone and the thick suite of mudstones and rare sandstones of the Brushy Basin Member lies a laterally continuous, distinctly cross-bedded pebbly sandstone with a notably scoured base that is tentatively correlated to the Westwater Canyon Member of the Morrison Formation. The unit is pale gray to white (10YR 9/1 to 8/1) and dominantly very poorly sorted vfU to cU grains, rounded to well rounded, mainly quartz but with 10-20% brownish gray cherts, <1-5% pinkish and yellowish cherts, <1% feldspars, and sparse (<<1%) pale greenish lithics. Pebbles are up to 2 cm across and composed of siliceous, dominantly varicolored cherts with lesser quartzites. Pebbles and very coarse sand grains are 0 to 10% of beds. Beds are thin to medium (0 to 30 cm thick) and lenticular with prominent and nearly ubiquitous cross-bedding. The unit as a whole is up to about 1 m thick, with an erosive undulatory basal contact (**Figure 3.6-3**).

### 3.6.3. Zuni Sandstone

*Fluvial facies (Jzf)*

As used in this report, the fluvial facies of the Zuni Sandstone consists of up to 8 m of interbedded fluvial and eolian sandstones, rare clayey mudstones, and sparse lenticular limestones forming bluffs that are only locally exposed beneath extensive landslides along the flanks of Cañon Seama (**Figure 3.6-4**). Sandstones are typically pale yellow (5Y 8/3 measured) with local light greenish gray hues, or are mottled reddish brown (5YR 5/3 measured) to red. Sands are principally moderately well-sorted vfU to fU grains, rounded, of quartz with sparse feldspars (<1%) and black lithics (cherts?, <1%). Poorer sorted muddy vfL to vfU sandstones, often mottled shades of pink or red, as well as locally pebbly coarse sand-grained channel fills are also present but rare. Sparse pebbles in channel fills are rounded, dark gray to dark brown, fine-grained siliceous clasts (cherts) up to 2 cm in diameter. Most commonly, beds are medium to thick (20-60 cm thick), tabular with undulatory contacts, and massive. Locally, tabular beds bear variably well-expressed cross-stratification that could be either fluvial or eolian in nature. Rare coarser-grained channel fills are commonly well cross-stratified, lenticular, and thinner (0-20 cm thick). Beds are moderately well indurated by a calcitic cement that is commonly visible under a hand lens as a thin, vitreous, clear to whitish coating along grains.

Mudstones are pinkish gray to reddish brown (5YR 5/3 measured), commonly exhibit clayey weathering textures, and bear vfU to fU sand grains. Mudstone beds are typically thin (<10 cm thick) and lenticular with undulatory bases, although locally a basal mudstone up to 1 m thick can be found. Mudstones are typically <10% of fluvial facies exposures, but can appear more abundant due to the tendency for muds to 'bleed' down a bluff to mask underlying sandstones, as well as due to the similar colors between mudstones and red-mottled sandstones (**FIGURE 3.6-5**). Sparse, thin (<20 cm thick), light gray limestones were also observed toward the top of the unit in isolated lenses.

The fluvial facies is locally capped by up to 1.2 m of light purplish gray (10R 5/2), thinly bedded and internally-laminated, muddy fine sandstone with white carbonate nodules (**FIGURES 3.6-6 AND 3.6-7**). Sand grains are poorly sorted vfL to fL, rounded, dominantly quartz with very sparse feldspars and black lithics. Beds are thin (0-10 cm thick), planar to undulatory, with undulatory internal laminae, possibly cross-laminations. White carbonate nodules are up to 3 cm across. The coloration, abundance of mud, and presence of carbonate nodules suggests the interval may be a paleosol developed into the top of the Zuni Sandstone.

*Main (eolian) facies (Jz)*

The Zuni Sandstone (*sensu* Anderson, 1993) is a yellowish, distinctly large-scale (eolian) cross-bedded quartzose fine-grained sandstone typically forming smooth, rounded exposures (Maxwell, 1982, 1990; this report). On this quadrangle, this unit is only exposed in the south of Cañon Seama, where it consists of well sorted fU to fL (sparse vfU) sands, rounded to well rounded, dominantly of quartz with sparse feldspars (<1-1%) and dark gray and pink lithics (cherts?, <1%). Beds are 0.5 to 1 m thick, massive to eolian cross-bedded, generally tabular in shape, and moderately well indurated by a calcitic cement. Sparse, fine to very fine (<0.1-0.4 mm diameter) nodules of white, chalky carbonate are visible under a hand lens, generally occurring on <<1% but very locally on as much as 3% of fresh surfaces. Elongate, oblate, and roughly spherical concretions are locally common. Deformation bands are typically rare. An exposed thickness of approximately 11 m was measured; the base of the unit is unexposed, and its total thickness in the subsurface is unconstrained on this quadrangle. Working on the quadrangle to the south, Maxwell (1976) indicates the Zuni Sandstone section is 50-90 m thick.

## 3.7. Subsurface units shown on cross-section

### 3.7.1. Jurassic Bluff Sandstone / Horse Mesa Member, Wanakah Formation (Jbh)

The eolian cross-bedded Zuni Sandstone overlies a massive sandstone variably referred to as the Bluff Sandstone (Anderson and Lucas, 1995, 1996; Maxwell, 1976) or the Horse Mesa Member of the Wanakah Formation (Condon, 1989). Maxwell (1976) indicates a thickness for this unit of 30-45 m.

### 3.7.2. Jurassic Summerville Formation / Beclabito Member, Wanakah Formation (Jsb)

Underlying the thick Zuni-Bluff sandstone section is a sequence of thinly bedded sandstones and mudstones variably correlated to the Summerville Formation (Anderson and Lucas, 1995, 1996; Maxwell, 1976) or the Beclabito Member of the Wanakah Formation (Condon, 1989). Maxwell (1976) indicates a thickness for this unit of 35-45 m.

### 3.7.3. Jurassic Todilto Limestone and Entrada Sandstone (Jet)

The Todilto Limestone consists of variably gypsiferous limestones (Anderson and Lucas, 1995, 1996; Maxwell, 1976). Maxwell (1976) indicates a thickness for this unit of <1-7 m. The Entrada Sandstone consists of eolian cross-bedded sandstones with variably silty and gravelly sandstones at the base. Maxwell (1976) indicates a thickness for this unit of 57-80 m.

### 3.7.4. Triassic Chinle Formation (Trc)

To the south, the top of the Chinle Formation consists of varicolored shaly siltstone and mudstone with few lenses of sandstone (Maxwell, 1976). The entirety of the Chinle Formation is 535-550 m thick in the Gottlieb #1 core hole drilled to the west on the Grants SE quadrangle (Cikoski, 2013).

# 4. Structure

The study area lies in the southeastern corner of the Colorado Plateau in the Acoma sag broad synclinal structural low area between the Zuni uplift to the west and the Sierra Lucero to the east. The sag is notably asymmetric, with a steep western limb and shallow eastern limb, with a trough along the north-plunging McCartys syncline, located to the east of the study area (Woodward, 1982). The Acoma sag grades northward into the Chaco slope of the San Juan basin, and abuts the Rio Puerco fault zone to the northeast (Woodward, 1982). The sag is principally thought to be a Laramide compressional feature (Woodward, 1982). Strata within the sag are generally only weakly deformed, and unconformably overlain and inset upon by Plio-Pleistocene volcanics. The area has also be subject to late Cenozoic extensional stresses associated with the Rio Grande rift.

## 4.1. Volcanic structures

The Cubero quadrangle lay between several predominantly basaltic volcanic fields. To the north lay the Plio-Pleistocene Mount Taylor volcanic field, which includes the Mount Taylor stratovolcano and surrounding basalt-capped high mesas (Goff et al., 2015), which reach southward just across the northern margin of the quadrangle. To the west lay the Pleistocene to Holocene Zuni-Bandera volcanic field, in which multiple basalt flows erupted from a chain of centers, some of which flowed into the Rio San Jose drainage; at least one flow may have crossed the study area and be present in the subsurface along the Rio San Jose (Channer et al., 2015; Drakos et al., 1991). Further away from the quadrangle to the south, the Cebollita Mesa area was designated as a separate volcanic field by Laughlin et al. (1993) on the basis of age and elevation (similar to Mount Taylor) and geochemisty (distinct from Mount Taylor). Finally, to the southeast lay the Sierra Lucero volcanic field. Some basaltic flows from the Mount Taylor area extend into the northernmost portion of the quadrangle, one flow from the Zuni-Bandera volcanic field may lie in the subsurface along the Rio San Jose, and a volcanic center inset against the Mount Taylor field lay in the center of the quadrangle.

### *Flower Mountain center*

The rounded Flower Mountain (also called Cubero Mountain) has long been recognized as a source area for the mesa-capping basalt flow that surrounds the summit. In previous reports, it is generally described in broad terms as a breccia pipe with associated scoria (Maxwell, 1990) or as a volcanic neck (Channer et al., 2015). Mapping as a part of this project subdivided the feature into subunits, providing greater detail into the evolution of the Flower Mountain volcano.

The youngest pre-volcanic deposits under Flower Mountain are alluvial deposits of an ancestral Rio San Jose, overlain by finer-grained tributary alluvium. This suggests the Flower Mountain volcano erupted onto an ancestral Rio San Jose floodplain or near to one. This alluvium lies unconformably upon shales of the Mancos that lie stratigraphically between the Cubero Sandstone Tongue (below) and Twowells Sandstone Tongue (above) of the Dakota (the Paguate Sandstone Tongue appears to be missing through this area). The oldest volcanic unit underlying Flower Mountain is a pyroclastic unit (Qbfp) that locally is inset into the underlying alluvium and Cretaceous strata. Due to poor exposure, the exact depth of this insetting is unknown, but extends at least 90 m below the top of the alluvium. Given that the Flower Mountain volcano appears to have erupted onto or near to a floodplain of an ancestral Rio San Jose, this inset relationship may be the result of a phreatomagmatic eruption excavating a crater in the alluvium and underlying Mesozoic strata underlying the floodplain. Similar pyroclastic deposits have been observed by the first author elsewhere that were similarly associated with phreatomagmatic (maar) craters around

Elephant Butte Lake (C.T. Cikoski, unpublished mapping on the Black Bluffs 7.5' quadrangle). Pyroclastics are also observed locally beneath the basalt flow of Flower Mountain.

Overlying the pyroclastics is a solid band of basalt (Qbfo) that is thickest directly over the inset pyroclastics and thins northward. This basalt grades upsection into a thick breccia, which is overlain by the main mass of scoria that forms the bulk of Flower Mountain (Qbfc). The lower basalt is inset up to 40 m into surrounding pre-volcanic alluvial deposits, and may be either a part of a volcanic plug (*sensu* Hallett, 1992) or be part of an *in situ* solidified magma pool (cf., Crumpler, 2003). The cinder unit is likely a combination of material erupted out of the volcanic center to construct the cinder cone and scoriaceous material accumulating in the throat of the volcano.

Two dikes are apparent in the south-southwest portion of Flower Mountain, both trending northeast-southwest and near vertical, one of which is mappable at the scale of this study (Qbfd). One dike can be followed through the underlying ancestral Rio San Jose alluvium into the Flower Mountain cinder unit, where the dike appears to merge into the cinder. The second, larger dike appears to merge with the lower solid basalt (Qbfo). Both are texturally similar to the lower basalt.

The flow that caps Cubero Mesa (Qbf) is elongate east-northeast-west-southwest and overlies in outcrop thin tongues of the pyroclastic unit (Qbfp) and the cinder unit (Qbfc). The trend of the flow, in combination with the presence of Rio San Jose gravels underlying the volcano, suggests the basalt may have flowed into an east-west elongate ancestral Rio San Jose valley. The eruption location is not preserved. Based on the distribution of the basalt flow, it seems likely that the flow erupted from point to the west-southwest of the peak of Flower Mountain: 1) the flow is widest in this location, thinning to the east; and 2) paleo slope is inferred to be down-gradient to the east, based on the interpretation of an ancestral Rio San Jose river valley and paleocurrent indicators in the ancestral Rio San Jose deposit, suggesting the flow would have originated nearer to its western extent.

Two ages have been reported for the basalt flow capping Cubero Mesa: 2.390 ± 0.114 Ma by the K-Ar method (Laughlin et al. (1993)) and 1.888 ± 0.012 Ma by the $^{40}Ar/^{39}Ar$ method (Channer et al., 2015). Notably, these ages do not overlap within error. Flows at the southern edge of the Mount Taylor volcanic field just north of the quadrangle boundary have reported $^{40}Ar/^{39}Ar$ ages of 2.22 ± 0.06 and 2.75 ± 0.03 Ma (Goff et al., 2015). These flows project to an elevation above that of the Flower Mountain flow, suggesting that they are older. The 2.22 and 2.39 Ma ages for the Mount Taylor and Flower Mountain flows barely overlap within error; if both are accurate, then the geomorphology suggests the true age of the Flower Mountain basalt lies at the lowest end of the K-Ar age range. Alternatively, the true age of the Flower Mountain flow is better represented by the $^{40}Ar/^{39}Ar$ age, which agrees well with the geomorphology and additional $^{40}Ar/^{39}Ar$ ages.

### *Zuni-Bandera volcanic field (ZBVF)*

The ZBVF lay entirely off-quadrangle to the west, but is worth mentioning as a basalt flow encountered in well logs may have erupted here and flowed eastward along the Rio San Jose. Drakos et al. (1991) document that this flow is of comparable elevation to the Laguna Pueblo flow exposed further west around the Pueblo of Laguna. Channer et al. (2015) acquired $^{40}Ar/^{39}Ar$ ages for this flow where exposed at Laguna (0.322 ± 0.011 Ma) and for a basalt encountered in a drill hole along the Rio San Jose to the west of the quadrangle by the town of Grants (0.325 ± 0.043 Ma) that are within error, suggesting they are the same flow. The combination of observations would be consistent with the Laguna Pueblo flow having erupted in the ZBVF and traversed the Rio San Jose valley to reach Laguna Pueblo, and to underlie the alluvium along the Rio San Jose in this quadrangle. Note that older published K-Ar ages for the Laguna Pueblo flow are significantly younger (0.11 ± 0.15 and 0.12 ± 0.15 Ma: Laughlin et al., 1993), but also substantially less precise, as is a 0.38 ± 0.25 Ma K-Ar age reported by Lipman and Menhert (1979). Laughlin et al. (1993) also suggested that the most likely source for the Laguna Pueblo flow was the ZBVF, although their correlation of the Laguna Pueblo flow to the El Calderon flow was refuted based on paleomagnetic grounds by Cascadden et al. (1997).

### *Mount Taylor volcanic field (MTVF)*

The MTVF lay mainly off-quadrangle to the north, but some flows extend southward from the main mass of the field into the northernmost extent of the Cubero quadrangle. Goff et al. (2015) provided a recent compilation geologic map covering most of the MTVF as well as numerous original $^{40}Ar/^{39}Ar$ ages for flows occurring throughout the field. Two ages reported for undivided flow units just north of the Cubero quadrangle boundary, 2.22 ± 0.06 and 2.75 ± 0.03 Ma, may be from flows that extend into the Cubero quadrangle.

The MTVF flows that extend into the Cubero quadrangle appear to have filled paleovalleys extending from a Pliocene-age Mount Taylor volcano. Paleovalleys are exposed along the western flank of the middle basalt-capped mesa occurring at the northern quadrangle boundary. Here, the oldest, particularly porphyritic flow(s) (Tbp1 and Tbp2) has a lenticular outcrop pattern, is inset into underlying Cretaceous rocks, and overlies a poorly-exposed, ~2 m thick basalt boulder conglomerate. The basalts in the conglomerate are coarse porphyries, which have been observed in-place further north within the MTVF (cf., Goff et al., 2015). These observations indicate the porphyry basalts backfilled paleocanyons carved by streams headed in the MTVF. The overlying fine-grained basalt (QTbf) has a more extensive map-pattern, but the distribution of the flow, as narrow northwest-southeast, north-northwest-south-southeast, and northeast-southwest mesa caps, suggests the flow was still confined to paleocanyons associated with the MTVF. The youngest flow, the plagioclase-phyric Qbp unit, likewise appears to be confined to broad paleocanyons.

Although none have been geochronologically dated or geochemically analyzed, the north-south trending dikes found in the central and eastern portions of the quadrangle could feasibly be radial dikes emanating from the heart of the MTVF to the north of the quadrangle. Alternatively, the attitude of these dikes may reflect Miocene to recent east-west directed tectonic extension and be unrelated to the MTVF.

### *Acomita Dike*

Laughlin et al. (1983) published K-Ar ages for three subparallel mid-Tertiary basaltic andesite dikes in the southern Colorado Plateau and Mogollon-Datil volcanic field area, including one dike between Acomita and Acoma which returned an age of 30.7 ± 1.4 Ma (Aldrich et al., 1986) and which they referred to as the Acomita dike. This dike strikes north-northwest and is exposed for approximately 10 km along strike, extending from north of Acoma to McCartys and beyond into the landslide-buried eastern flank of Horace Mesa. Several smaller similar-textured subparallel dikes follow this larger continuous feature. Aldrich et al. (1986) utilized this and several subparallel, similar-aged dikes to interpret a regional east-northeast-west-southwest extension direction. Chamberlin et al. (2002), in contrast, suggested that the Acomita dike may be a part of a regional radial dike swarm associated with a late Oligocene magmatic system inferred to underlie a chain of calderas extending west-southwest from the town of Socorro. Both agree that the dike is an important local expression of regional geologic processes.

## 4.2. Tectonic structures

### 4.2.1. Faults and folds

Only a few map-scale faults are apparent in the study area, principally in the southern half of the study area. Both compressional and extensional features are apparent.

*Transpressional deformation – Woods Mesa fault and fold*

In the southwestern corner of the study area lies the northeast-trending Woods Mesa fault that dies upsection or to-the-northeast in a southeast-facing monoclinal fold. An exposure of the Woods Mesa fault just southwest of where it dives into the monocline reveals a brecciated fault core approximately 30 cm thick surrounded by a damage zone that extends approximately 2 m away from the core (**FIGURE 4.2-1**). The fault core trends approximately S44W/84NW (**FIGURE 4.2-2**). Within the damage zone, a pervasive jointing or fracturing is apparent to either side of the core, with an average orientation of S25W/77W. Striations on a plane parallel to the fault core are oriented 06° to N47E, while striations on one of the adjacent fractures trend 69° to N07W (average of 4 measurements; **FIGURE 4.2-2**). A small normal fault is also exposed in the area with approximately 5 cm of displacement, with a fault plane of N61W/86NE and striations trending 77° to S77E. Fractures in the damage zone do not cross the main fault core.

Assuming the main fault and all fractures are genetically related and formed synchronously, the sense of slip and general stress regime can be inferred. The striae on a small plane within and parallel to the brecciated fault core suggested dominantly strike-slip motion. Strata offsets apparent at the surface indicate the northwest side (hanging wall) is upthrown, indicating reverse slip. Assuming reverse slip along the trend of the aforementioned striae, left-lateral motion would be inferred. The pervasive SSW-striking joints or fractures in the damage zone resemble "feather joints" or possibly low-offset Riedel shears. Given the attitude of these joints with respect to the main fault core, left-lateral motion would again be inferred (see **FIGURE 4.2-1**). If these joints are Riedel shears, the slip vector along the main fault core should be a line in the fault trend perpendicular to the intersection of the shears/joints and the main fault trend. This line trends 22° to N42E, comparable to the attitude of striae measured on a small plane within the fault core, though with a notably steeper plunge. Again, left-lateral and reverse oblique-slip is inferred.

The sense of offset across the pervasive joints or R-shears was not apparent in the field. However, if these are Riedel shears, the sense of offset should be the same as the main fault, or left-lateral. Left-lateral shearing along the trend of striations apparent on one of the fracture planes would indicate an additional component of reverse dip-slip, consistent with the left-lateral reverse slip on the main fault. Reverse slip along the joints and main fault plane indicate shortening in a roughly SE-NW direction. The small normal fault with steeply dipping striae indicates lengthening in a roughly NE-SW direction. Consideration of the effects of left-lateral shearing of an ellipse (**FIGURE 4.2-2**) indicates that such mutually perpendicular lengthening and shortening directions could be consistent with left-lateral shearing.

Thus, all measurements and observations at the fault outcrop are consistent with left-lateral transpressional deformation across the main fault core. The most likely deformation event to have produces this stress regime was the Laramide orogeny. Note that Laramide deformation may have progressed in distinct stages (cf., Cather, 2004) and that the area was subject to subsequent extension associated with the Rio Grande rift. Therefore it is not a certainty that the main fault, damage zone joints, and normal fault all developed during the same stress regime. The analysis presented here merely indicates that all three structures *could* be consistent with a single sinistral transpressive regime.

To the northeast, the Woods Mesa fault seemingly terminates in a monoclinal fold. This broad fold can be followed northeastward almost to the Rio San Jose valley, but terminates approximately 1-1.7 km southwest of the valley edge. Along strike with the fold is an anomalous region of northeast-striking joints that contrast with the dominant north-south and east-west trends of joints through the remainder of the map area. Further along strike lay the Flower Mountain volcano, and yet further along the same trend lay the northeast-southwest elongate Picacho Peak plug (Hallett et al., 1997). This trend cannot be readily followed further to the northeast nor to the southwest, and hence does not appear to have regional significance.

*Extensional features*

South of the aforementioned Woods Mesa fault-and-monocline lay an east-northeast to east-west trending fault. Strata offset indicates down-to-the-north displacement. An outcrop of the fault zone reveals a "keystone horst" in the immediate footwall of the main fault plane bounded by several seemingly conjugate small-offset synthetic and antithetic faults (**FIGURE 4.2-3**). Striations were not observed on the main fault plane, but were observed on both synthetic and antithetic faults (**FIGURE 4.2-4**). Striations and conjugate pairing is consistent with essentially pure normal dip-slip offset across the fault. The inferred local extension direction is NNE-SSW to possibly N-S. This extension direction is unusual for the Rio Grande rift, which exhibits dominantly east-west extension, and may be a result of local stress fields. Aldrich et al. (1986) note that this general area, which they interpret to be a transition zone between the Colorado Plateau and Rio Grande rift, shows evidence for local least principal horizontal stress directions varying from north-south to northwest-southeast to east-northeast-west-southwest, supporting the interpretation that local stress fields may not be reflective of the overall east-west Rio Grande rift extension orientation.

The Acomita dike of Laughlin et al. (1983) dips nearly vertically, strikes NNW-SSE, and appears to collocate with a down-to-the-southwest normal fault. This is particularly apparent further west on the McCartys quadrangle (Maxwell, 1977; C.T. Cikoski, unpublished data). The dike was used, in combination with additional dike attitudes and ages, to infer a northeast-southwest extensional direction at the time of emplacement (K-Ar age of 30.7 ± 1.4; Aldrich et al., 1986). Similarly, the set of north-south trending dikes of uncertain age may reflect the east-west extensional stresses of the Miocene to present Rio Grande rift. Alternatively, the north-south dikes may be radiating from the Mount Taylor stratovolcano.

Drakos et al. (1991) inferred a small graben underlying Cañon Seama based on the elevation of a basalt flow in drill logs from Risser and Lyford (1983) for wells drilled along the Rio San Jose floodplain. The basalt within the inferred graben is down-dropped 4 to 6 m relative to the basalt outside the graben. Bedrock mapping for this study found additional evidence for a small down-to-the-west fault along the east side of Cañon Seama, particularly in the trend of the Zuni Sandstone\Morrison Formation contact. Approximately 1.8 km south of the town of Seama, the contact can be found at 1,843-1,848 m above sea level elevation at the base of the western flank of Seama Mesa, but the same contact crops out of the landslide terrain at about 1,862 m above sea level a few hundred meters to the southeast. The contact attitude was measured to dip 2° to the west-northwest in the valley floor outcrop and 2° to the southwest in the hillside outcrop. Although some of the decrease in elevation between the two outcrops could be the result of the dip of the contact, the dip can only account for at most approximately 10 m of elevation change (2° along a 300 m horizontal distance). This would leave a small discrepancy that could be accounted for with a small fault hidden in the landslide terrain. Further south, along the southern boundary of the quadrangle on the eastern margin of the west fork of Cañon Seama, the same contact can be observed to "dive" anomalously from south to north. From the quadrangle boundary northward to about 400 meters into the quadrangle, the Zuni-Morrison contact behaves as a subhorizontal plane, but north of 400 m the contact descends to the north-northeast at approximately 9°, eventually plunging into the subsurface at approximately 700 m north of the quadrangle boundary. To the east of this outcrop, however, the contact again occurs at the surface. These relations could be explained with a small down-to-the-west fault with southward-decreasing magnitudes of offset. We interpret the Zuni-Morrison contact variability along the east margin of Cañon Seama to be the product of small offset faulting, and continue this fault into the Rio San Jose floodplain to be the eastern boundary of the Cañon Seama graben of Drakos et al. (1991). Alternatively, the observed scatter in the elevation of the Zuni-Morrison contact could be the result of landsliding through this area. No bedrock evidence was found for a fault along the western margin of Cañon Seama. The Cañon Seama graben as inferred from Quaternary and bedrock evidence trends north-northeast to north-south.

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# 6. Tables

**Table 1. Summary of Soil Morphology Cubero Quadrangle mapping (described by P. Drakos and J. Riesterer)**

| Horizon | Depth (cm) | Gravel (%) | Dry Color (Matrix) | Moist Color (Matrix) | Texture | Structure | Dry Consist-ence | Wet Consist-ence | Argillans | $CaCO_3$ | $CaCO_3$ Stage | Lower Horizon Boundary | Preliminary Age Estimate (years BP)[1] | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Location: Arroyo cut into Cañon Seama valley floor; Qal description. UTM Zone 13, 3877332m N., 268304m E., NAD 83 Described 3/8/2016** | | | | | | | | | | | | | | **Field location CUB-16-01** |
| A | 0-10 | | 10YR5/3 | | | m | | | n.o. | es-ev | | | Mid-Late Holocene | |
| Bw | 10-30 | | 10YR6/4 | | | 2msbk | | | n.o. | | | | | Sandy gravel with reworked CaCO3 nodules |
| C | 30-60 | | 10YR6/4 | | | m | | | n.o. | | | | | Sand with gravel lenses |
| Ab1 | 30-130 | | 10YR5/3 | | | 2msbk-pr | | | n.o. | es-ev | | | | Silty vfs with charcoal |
| Cox | 130-330 | | 10YR5/4 | | | m | | | n.o. | es-ev | | | | Sand with scattered pebbles, local gravel lenses, predominant ss clasts, minor chert and ls |
| Bwb2 | 330-390 | | 7.5YR5/6 | | | 2msbk | | | n.o. | e | | | Early-Mid Holocene | |
| Bkb2 | 390-440+ | | 7.5YR6/3 | | | 2m-csbk | | | n.o. | ev | I | | | CaCO3 filaments abundant throughout |
| **Location: Eolian deposit on Hill 6293. UTM Zone 13, 3880800m N., 263910m E., NAD 83 Described 3/9/2016** | | | | | | | | | | | | | | **Field location CUB-16-5** |
| AC | 0-10 | | 7.5YR5/6 | | | m | | | n.o. | e | | | | Well sorted, rounded-subrounded fine qtz sand |
| Bkb1 | 10-40+ | | 7.5YR5/4 | | | | | | n.o. | ev | I | | | Disseminated CaCO3 and small (<2 mm) nodules; Well sorted, rounded-subrounded fine qtz sand |
| **Location: Arroyo cut into valley floor of "Alaska" canyon; Qal description. UTM Zone 13, 3877944m N., 263292m E., NAD 83 Described 3/9/2016** | | | | | | | | | | | | | | **Field location CUB-16-11** |
| A | 0-50 | | 10YR4/4 | | | 1m-csbk | | | n.o. | es | | | | Well sorted, rounded-subrounded fine qtz sand with minor lithics; eolian |
| IIBkb1 | 50-80 | | 10YR5/4 | | | 2msbk | | | n.o. | es | | | | Qc; sandy ang-subang pebble-cobble ss gravel |
| IIIBC | 80-560 | | 10YR6/4 | | | 2m-csbk | | | n.o. | es | | | | Qtz lithic fs with rare gravel lenses, scattered charcoal. Overlies Kd sandstone. |
| **Location: Arroyo cut into valley floor of unnamed drainage SE of Acomita; Qal description. UTM Zone 13, 3881315m N., 265886m E., NAD 83 Described 3/10/2016** | | | | | | | | | | | | | | **Field location CUB-16-14** |
| A | 0-20 | | 10YR5/4 | | | m | | | n.o. | es | | | Holocene/Late Holocene | Eolian sand; well sorted an rounded qtz fs |
| Bk1 | 20-80 | | 7.5YR5/4 | | | 2m-csbk | | | n.o. | es-ev | | | | Some CaCO3 filaments on ped faces; qts fs with minor lithics; scattered gravel lenses |
| Bk2 | 80-190 | | 10YR6/4 | | | 1-2msbk | | | n.o. | es-ev | | | | |
| IICb1 | 190-260 | | 2.5Y-10YR6/4 | | | m | | | n.o. | | | | | Clast supported ang ss cobble and boulder gravel+ang-rounded ss and qtzite pebbles; Qc |
| IIIBkb2 | 260-500 | | 10YR5/4 | | | 1-2msbk | | | n.o. | es-ev | | | | Subround-subang qtz lithic fs; some snails present, rare angular clasts @ 3.9 m |
| IVCb2 | 500-530 | | 10YR-7.5YR5/4 | | | m | | | n.o. | | | | | Stratified sand and disc-shaped granule to pebble gravel; Qal |
| VBkb3 | 550-640+ | | 7.5YR5/4 | | | 2msbk | | | n.o. | es-ev | | | | Mod. Sorted subang. Silty vfs-fs, qtz lithic sand |
| **Location: Arroyo cut into distal Qf3 surface at 6460 ft, NW of Picacho Pk. Described 7/27/1989** | | | | | | | | | | | | | | |
| AC | 0-18 | <2 | 10YR5/3 | 10YR5/3 | s | m | lo | so,po | n.o. | es | | gs | Middle-late Pleistocene overlain by Holocene | Eolian sand |
| BCk | 18-42 | | 10YR6/4 | 10YR4/4 | sl | 2msbk | sh | ss,ps | n.o. | es | I | cs | | Some 2mm nodules |
| Btkb1 | 42-120 | 10 | 7.5YR4/6 | 7.5YR4/4 | scl | 2-3msbk | sh | s,p | 1ncopobr | es | | cs | | |
| Bkb1 | 120-165 | 10 | 7.5YR6/4 | 7.5YR5/4 | scl | 2msbk | sh-h | s,p | n.o. | | 1+ | gs | | CaCO3 filamants, discontinuous to continuous coatings on clasts |
| **Location: Arroyo cut into distal Qf3 surface at 6380 ft, NE corner of Quad. UTM Zone 13, 3888789m N., 271292m E., NAD 83 Described 4/28/2016** | | | | | | | | | | | | | | **Field location CUB-16-21** |
| A | 0-20 | 40-50 | 10YR4/3 | | s | 1fgr | | | n.o. | non | - | gs | Middle-late Pleistocene overlain by Holocene | Locally derived, poorly sorted angular, vf-vc volcanic lithic sand matrix and poorly sorted pebble-cobble gravel |
| Bw | 20-70 | 40-50 | 10YR4/2 | | s | 2msbk | | | n.o. | non | - | aw | | |
| Bt | 70-120 | 5-10 | 5YR5/6 | | | 3msbk | | | 1nbrpo | non | | cs | | Moderate-poorly sorted , subangular vf-f qtz sand; pebble-cobble gravel |
| Bk | 120-200+ | <10 | 7.5YR8/2 | | | m | | | n.o. | ev | II-III | | | 2+ m = CaCO3-cemented cobble gravel |
| **Location: Arroyo cut into Qf3 surface at 6370 ft, mouth of Cañon Seco. UTM Zone 13, 3887997m N., 266419m E., NAD 83 Described 4/28/2016** | | | | | | | | | | | | | | **Field location CUB-16-26** |
| AC | 0-60 | <2 | 10YR4/4 | | | 1msbk | | | n.o. | non | - | aw | Middle-late Pleistocene overlain by Holocene | |
| Ab1 | 60-75 | <2 | 10YR4/3 | | | 2msbk | | | n.o. | es | I | cs | | CaCO3 filaments |
| Btkb1 | 75-130 | <2 | 7.5YR5/6 | | | 2mpr | | | 2npobrpf | ev | I+ | aw | | CaCO3 filaments and sparse 2-3 mm nodules |
| IIBkb1 | 130+ | ~40-50 | Bouldery deposit with sandy lenses near bottom of arroyo; boulders appear to have had continuous CaCO3 coatings that have been scoured | | | | | | | | | | | |
| **Location: Arroyo cut into Qf3 surface at 6350 ft, S. of Cañon Seco. UTM Zone 13, 3887467m N., 264780m E., NAD 83 Described 4/29/2016** | | | | | | | | | | | | | | **Field location CUB-16-29** |
| A | 0-8 | 10 | 10YR4/4 | 10YR3/4 | s | 1msbk | so | so,po | n.o. | non | - | | | Reworked clasts; poorly sorted, subrounded qtz lithic sand. |

| Table 1. Summary of Soil Morphology Cubero Quadrangle mapping (described by P. Drakos and J. Riesterer) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizon | Depth (cm) | Gravel (%) | Dry Color (Matrix) | Moist Color (Matrix) | Texture | Structure | Dry Consistence | Wet Consistence | Argillans | $CaCO_3$ | $CaCO_3$ Stage | Lower Horizon Boundary | Preliminary Age Estimate (years BP)[1] | Notes |
| Bw1 | 8-60 | ~30 | 10YR5/4 | 10YR3/4 | sl | 2msbk | so | ss,ps | n.o. | es | - | | Middle-late Pleistocene overlain by Holocene | silty vfs (eolian?) and gravel lag |
| Bw2 | 60-106 | <2 | 10YR5/6 | 10YR4/6 | s | 2msbk | sh | so,po | n.o. | non | - | | | Well sorted, subrounded, qtz lithic fs. |
| Btkb1 | 106-146 | 20 | 7.5YR4/4 | 7.5YR4/4 | scl | 2-3msbk | sh | s,p | 1nbrpo | es | I | | | CaCO3 filaments; moderately sorted, subangular, qtz lithic fs-ms. |
| Bkb1 | 146-281 | <5 | 10YR5/4 | 10YR4/3 | sl | 2msbk | h | so, ps | n.o. | ev | I+ | | | CaCO3 filaments and rare nodules |
| IICox | 281-421+ | Clast supported pebble to cobble gravel with scattered boulders up to 1 m; weak imbrication to south, predominantly volcanic clasts | | | | | | | | | | | | |
| **Location: Arroyo cut into Qf4 surface at 6300 ft, S. of Cañon Seco. UTM Zone 13, 3887353m N., 265529m E., NAD 83 Described 4/29/2016** | | | | | | | | | | | | | | **Field location CUB-16-32** |
| AC | 0-30 | <2 | 10YR5/4 | | | | | | n.o. | e | - | | | Mod. sorted, subrounded-rounded qtz lithic fs-ms with minor silt. |
| Ab1 | 30-40 | <2 | 10YR4/4 | | | | | | n.o. | non | - | | | Mod. sorted, subrounded-rounded qtz lithic fs-ms |
| Bwb1 | 40-70 | <2 | 10YR5/3 | | | | | | n.o. | non | - | | | Mod. sorted, subrounded-rounded qtz lithic fs-ms |
| Ab2 | 70-80 | <2 | 10YR4/3 | | | | | | n.o. | non | - | | | Mod. sorted, subrounded-rounded qtz lithic fs-ms with minor silt. |
| Bwb2 | 80-160 | <2 | 10YR5/4 | | | | | | n.o. | es | I+ | | | Mod. sorted, subrounded-rounded qtz lithic fs-ms. |
| Bkb3 | 160-210 | <2 | 7.5YR5/4 | | | | | | n.o. | es | I+ | | | Mod. sorted, subrounded-rounded qtz lithic vfs-ms with common basalt lithics. CaCO3 filaments and scattered nodules. |
| IICoxb3 | 210-235 | Clast supported imbricated subangular to angular pebble to cobble basalt gravel. | | | | | | | | | | | | Contact with Km at 235 cm; lt gray shale |
| Notes: | | | | | | | | | | | | | | |
| [1]Age estimates based on relative soil development and comparison with soils in similar climate regimes and parent material for which age constraints are available. See Machette (1985), Drake [Drakos} et al. (1991) | | | | | | | | | | | | | | |
| See key for explanation of symbols. | | | | | | | | | | | | | | |

Key to symbols used in descriptions of soil morphology (from Birkeland (1984) and McDonald (1996))

**Structure**

| **Grade** | **Size** | **Type** | **Other** |
|---|---|---|---|
| 1 = weak | vc = very coarse | sbk = subangular blocky | : = parting to (e.g. pr:pf) |
| 2 = moderate | c = coarse | abk = angular blocky | |
| 3 = strong | m = medium | pr = prismatic | |
| | f = fine | pl = platy | |
| | | sg = single grain | |
| | | m = massive | |

**Consistence**

| **Dry** | **Moist** | **Wet - Stickiness** | **Wet - Plasticity** |
|---|---|---|---|
| lo = loose | lo = loose | so = non sticky | po = non-plastic |
| so = soft | vfr = very friable | vss = very slightly sticky | vps = very slightly plastic |
| sh = slightly hard | fr = friable | ss = sticky | ps = slightly plastic |
| h = hard | fi = firm | s = sticky | p = plastic |
| vh = very hard | vfi = very firm | | |

**Cutans**

| **Abundance** | **Thickness/(Distinctness)** | **Location/Type** | **Type** |
|---|---|---|---|
| n.o. = none observed | n = thin (faint) | po = along pores | man = mangans |
| | mk = moderately thick | | |
| v1 = very few (< 5%) | (distinct) | co = coating gravel, ped faces | skel = skeletans |
| 1 = few (2 - 25%) | k = thick (prominent) | br = bridging grains | si = silans |
| 2 = common (25 - 50%) | | pf = along ped faces (as co + br) | |
| 3 = many (50 - 75%) | | pr:pf along prismatic ped faces | |
| 4 = nearly continuous (75+%) | | bk:pf along blocky ped faces | |
| | | Lam = lamellae | |
| | | Non-lam = interspace between lamallae | |
| | | PI: ped interior | |
| | | prfc: pressure faces | |
| | | irg = irregular shape | |

**Horizon Boundary**

| **Thickness** | **Topography** | **Carbonate effervescence in HCl** |
|---|---|---|
| a =abrupt (< 2.5cm) | s = smooth | none = non-effervescent |
| c = clear (2.5 - 6cm) | w = wavy | e = slightly effervescent |
| g = gradual (6-12.5cm) | i = irregular | es = strongly effervescent |
| d = diffuse (> 12.5 cm) | b = broken | ev = violently effervescent |

**Texture**

| | |
|---|---|
| s = sand | sil = silt loam |
| ls = loamy sand | scl = sandy clay loam |
| sl = sandy loam | sicl = silty clay loam |
| l = loam | cl = clay loam |

# 7. Figures