Preliminary Geologic Map of the Grants Quadrangle, Cibola County, New Mexico (Year 2 of 2-Year)

By

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Open-file Digital Geologic Map OF-GM 224

Scale 1:24,000

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PRELIMINARY GEOLOGY OF THE GRANTS QUADRANGLE, CIBOLA COUNTY, NEW MEXICO

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Central and West Grants Ridges, looking west for the west edge of East Grants Ridge. Central and West Grants ridges are the two mesas along the center of the photo. Hummocky terrain to the left and right sides of the mesas belongs to a landslide complex. Sporadic yellow and red outcrops are Mesozoic sediments. Houses along the left edge of the photo belong to the town of Grants.

INTRODUCTION

Grants quadrangle is located just west of the composite stratovolcano Mount Taylor and encompasses the town of Grants in west-central New Mexico. The Mount Taylor-Grants area lies within the boundary between the Colorado Plateau to the northwest and the Rio Grande Rift to the east. The geology of the Grants quadrangle includes Mesozoic sedimentary rocks, Pliocene volcanic rocks related to Mount Taylor and younger sediment. The topography consists of high, steep-sided mesas such as Grants Ridge and Horace Mesa and broad, relatively flat alluvial canyon floors north and south of Grants Ridge and surrounding Grants. The southwest corner of the map includes part of the El Calderon and Paxton Springs lava flows, as well as minor outcrops of Paleozoic limestone. Cretaceous units are exposed along the northern and western flank of Horace Mesa, which dominates the eastern third of the quadrangle. The quadrangle is bisected from east to west by East Grants Ridge, which is capped by basaltic cinder and flows overlying rhyolite flows and tuffs and Upper Cretaceous strata; Grants Ridge, overlying Middle to Upper Jurassic strata; and West Grants Ridge, which is capped by a trachybasalt (Laughlin et al., 1993) and covers Upper Triassic strata. The town of Grants is located in the center and southwest corner of the quadrangle. Grants quadrangle was previously mapped in the 1960s (Thaden et al., 1967).

ACKNOWLEDGMENTS

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PALEOZOIC AND MESOZOIC SEDIMENTARY STRATA

Paleozoic and Mesozoic sedimentary rocks are preserved across much of the Grants quadrangle area. In the southwestern corner of the map area, small outcrops of the Permian San Andres Formation occur along US Highway 5. The San Andres Formation is a thin to medium bedded pale gray to buff dolomitized limestone with no obvious fossils. A discrete zone of black and white banded chert occurs near the top of the outcrops and may be correlative to a similar zone of banded chert observed at the top of the Bonney Canyon Member of the San Andres Formation in the Sacramento Mountains in southeastern New Mexico. Low amplitude and long wavelength flexures occur along the length of the San Andres Formation observed in the roadcuts along Highway 53.

Mesozoic strata include the Upper Triassic Chinle Group, Middle to Upper Jurassic strata and Upper Cretaceous strata. The Chinle Group here consists of red to purple mudstone with small, laterally discontinuous lenses of grayish purple coarse sandstone to conglomerate. Locally, Chinle Group outcrops are color mottled with purple, gray, green and red. Outcrops of

Upper Triassic strata occur around the edges of West Grants Ridge and are mostly covered by land-slide complexes or by urban development. Due to the lack of exposure, we do not identify these units at the formation level. Middle to Upper Jurassic strata exposed in the map area include the Entrada Sandstone, the Todilto Formation and the Morrison Formation and these occur along the flanks of Grants Ridge in the center of the map. As with the Triassic strata to the west, the Jurassic strata are mostly covered by large land-slide complexes. Linework for some of the exposures of Jurassic and Cretaceous strata around Grants Ridge is taken from Thaden et al. (1967).

Cretaceous strata are exposed at East Grants Ridge and along the flank of Horace Mesa in an outcrop belt trending mostly north-south. Much of the outcrop is covered by land-slide complexes. Here we follow the Cretaceous stratigraphy used by Goff et al. (2008) for Lobo Spring quadrangle to the east. The oldest Cretaceous strata exposed are the Dakota Sandstone which outcrops as a long, somewhat arcuate hogback through the center of the map area. These strata dip 30-35° to the east. Above the Dakota Sandstone is the Mancos Shale, which is mostly covered in the map area. The upper Mancos Shale is interbedded with the three tongues of the Gallup Sandstone (in ascending order): Gallup Lower, Gallup Upper and Gallup Main Body. All three tongues of the Gallup Sandstone are buff to gold fine to medium grained quartz arenites that have a distinctive rounded weathering pattern. The lower two tongues vary in thickness whereas the upper tongue is thick throughout. Overlying the Gallup Sandstone is the Dilco Coal Member, which includes thin, blocky, green to tan sandstone bodies, siderite nodules and dark gray coal deposits. The Dilco Member represents deposition in terrestrial conditions. The Stray Sandstone lies above the Dilco Member and is a dark orange to tan couplet of two sandstone bodies that locally has a chert and quartzite conglomerate on the top of the upper sandstone body. The Stray Sandstone is overlain by the Mulatto Tongue of the Mancos Shale, a distinctive mustard yellow shale that grades upwards into laminated sandstones and siltstones with birrows and local accumulations of pelecypod fossils. The Dalton Sandstone sits above the Mulatto Tongue and the lowermost sandstone beds in the Dalton Sandstone often contain abundant pelecypod casts and molds. The Dalton Sandstone is comprised of two main sandstone bodies: the lower sandstone is yellowish orange and the upper sandstone is white and somewhat less cemented than the lower sandstone. Above the Dalton Sandstone is the Gibson Coal Member, a very thick terrestrial sequence of coal, shale and minor sandstone. Mudclast conglomerates are common at the base of sandstone beds. Siderite concretions are also common.

IGNEOUS ACTIVITY

Mount Taylor is a composite stratovolcano of intermediate composition. The first geologic map of the Mount Taylor-Grants area was published in 1938 by the U.S. Geological Survey (Hunt, 1938) and subsequent efforts included a spate of mapping at 1:24,000 scale in the 1960s. Volcanism associated with Mount Taylor began around 3.8 Ma (early Pliocene) and ended between 2 Ma and 1.5 Ma (Perry et al., 1990; Goff et al., 2008). Flows extending from the flanks of the volcano have preserved a regional pediment surface identified as Pliocene in age (Goff et al., 2008) that developed during a time of base-level stability and growth of pediment surfaces across west-central New Mexico. In the Grants quadrangle area, Horace Mesa on the east side of the map preserves part of this pediment surface. The three Grants Ridges, however, likely preserve a paleovalley carved into this pediment (Kerr and Wilcox, 1963; Keating and Valentine, 1998).

Volcanism began on the Grants quadrangle with the eruption of the Grants Ridge Tuff, from which Goff et al. (2008) extracted and $^{40}Ar/^{39}Ar$ dated obsidian clasts at 3.26 ± 0.04 Ma (Figure 1, 2). Small outcrops of this tuff are found along the western margin of Horace Mesa beneath the basalt cap, while a large body of tuff underlies the basaltic and rhyolitic flows of East Grants Ridge. Kerr and Wilcox (1963) and subsequent authors suggest this large body, which map patterns indicate is laterally juxtaposed against the Mesozoic strata, filled a paleovalley carved into the underlying Mesozoic rocks. Our data supports this idea: 1) attitudes of tuff bedding throughout the area have shallow dips (<10°) to variable directions; the dip direction variability may be a result of local deformation of the soft tuff strata by the overlying dense basalt flows and/or of local volcanic structures associated with eruptions of the tuff, rhyolite dome, and basalts, but the lack of a consistent dip direction argues against large-scale post-emplacement deformation; and 2) we observed in outcrop the depositional basal contact circa 246720 m E, 3900320 m N (NAD27, Zone 13), where it dips 20-25° to the SSE, and where a basal tuff bedding attitude of 34° to the east was measured; given the apparent lack of large-scale post-emplacement deformation of the tuff, it seems these moderately-dipping basal attitudes are primary in nature and not a result of deformation. These observations suggest the tuff draped over and subsequently buried a paleoslope. Keating and Valentine (1998) suggest this paleovalley likely trended northeast, controlled by the underlying San Rafael fault. Keating and Valentine studied the stratigraphy of the tuff in detail, and concluded the tuff consists of pyroclastic fallout, surge, and flow deposits from at least two eruptive sequences, interbedded with lesser alluvium.

Figure 1. Basaltic cinder cone with central columnar mass, overlying the tuff and rhyolite of Grants Ridge, looking north. White material to left and right of central mass is tuff, brown cliffs to far right in hillside are the rhyolite. West flank of cinder cone is the dark red triangular wedge to left of central columnar mass. Dark cliffs on far left is the mesa-capping basalt flow. Dark yellow outcrops in lower half of photo are Cretaceous rocks.

Figure 2. Contact of Grants Ridge Tuff overlying Mesozoic sediments, looking west. White outcrops throughout photo are tuff, and the yellow outcrops on right side are the Mesozoic sediments. Contact dips ~20° to the south (left side of photo). While the contact and basal bedding attitudes in the tuff dip moderately south to east, bedding attitudes are dipping <10° just up section from photo, suggesting the dip of the contact is not a result of post-emplacement deformation.

The eruption of the domal rhyolite of Grants Ridge followed the eruption of the tuff. K-Ar ages of 3.3 ± 0.3 and 3.34 ± 0.16 Ma have been reported for this rhyolite (Bassett et al., 1963; Lipman and Mehnert, 1978), suggesting the tuff and rhyolite are a part of the same volcanic system. Thickness trends indicate the vent for the rhyolite lay at the east end of East Grants Ridge, ~500 m east of the quadrangle boundary on the Lobo Springs quadrangle (Goff et al., 2008). The dome is strongly flow-banded, commonly with steep attitudes that dip away from the center of the dome. Obsidian is common to the northern flank and top of the dome by the contacts with the underlying tuff and overlying basalt. Map patterns and local exposures suggest the dome is inset upon the tuff, possibly as a result of eruption-related subsidence or post-emplacement compaction causing the dome to subside into the underlying tuff.

The tuff and rhyolite are overlain by a basaltic flow that appears to have originated from a cinder cone on the south side of East Grants Ridge and flowed west-southwest along the trend of the three Grants Ridges, possibly following a paleovalley controlled by the underlying San Rafael fault (Kerr and Wilcox, 1963). Kerr and Wilcox (1963) suggest the "tadpole" shape of West Grants Ridge may be the result of a confluence of two paleovalleys. Laughlin et al. (1993)

analyzed a sample from West Grants Ridge, determining a K-Ar age of 2.57 ± 0.13 Ma. To the east of the cinder cone, the basalt flow thins rapidly from the northern and southern margins of East Grants Ridge toward the center, suggesting the basalt on-lapped a paleotopographic high associated with the rhyolite dome. Monocline-like warping of the trend of the basalt on the west side of East Grants Ridge may also be a result of underlying paleotopography. The cinder cone itself was studied in detail by Crumpler (2003), who suggested the mass of columnar basalt exposed at 248140 m E, 3899360 m N is the central lava pond, solidified in place, while the drainage in the cinder cone immediately north of this mass may be the breach in the cone through which the lava escaped.

An anomalous zone of basaltic cinder and breccia inset upon the Mesozoic strata occurs at the west end of East Grants Ridge in a small drainage. Kerr and Wilcox (1963) referred to these rocks as intrusive “basaltic breccia plug and associated lamprophyre dikes” and suggested they are the youngest igneous rocks of East Grants Ridge. However, we followed a distinctive basaltic breccia band from the floor of the drainage, where it intercalates with the surrounding cinder, up to the wall of the drainage, where it underlies the mesa-capping basalt in outcrop, indicating the basaltic breccia and associated cinder is older than the capping basalt flow (Figure 3). We also did not observe any dike-like morphologies in this area, and are unaware of any chemical analyses of these rocks. Unfortunately, the basaltic mass is surrounded by colluvium, such that any intrusive margin textures are obscured. While these rocks very well may be intrusive, we choose to use the descriptive term ‘inset’ instead of the genetic term ‘intrusive’ to describe them, given our uncertainty in their origin.

Figure 3. Overlooking the inset cinder unit, Ttci, looking north-northeast. Yellow outcrops just left of center and in background on right side are Mesozoic, which is capped by black basalt. Brown outcrop below the Mesozoic is the Ttci

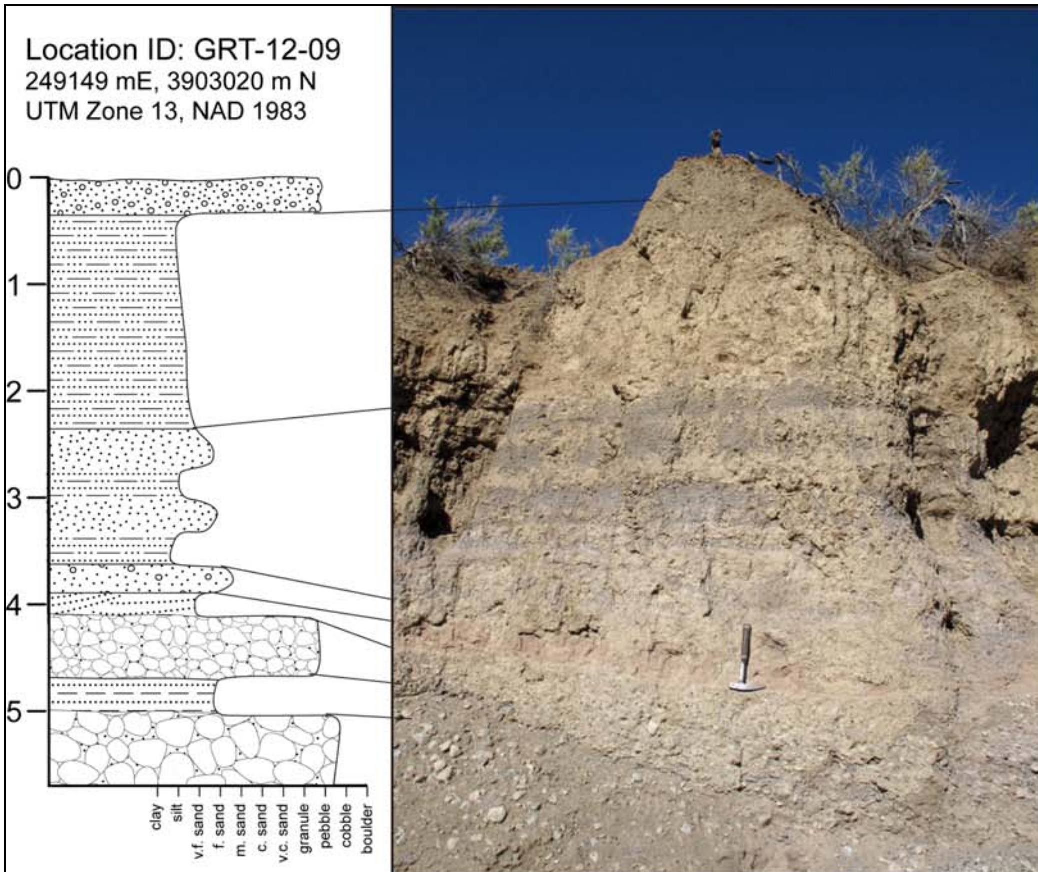
unit. The contact between the Ttci and Mesozoic units appears to be near-vertical and trends east-west through the hillside.

No age controls exist for the basalts capping Horace Mesa on the Grants quadrangle, but samples from the Lobo Springs and McCartys quadrangles have yield K-Ar ages of 3.73 ± 0.09, 2.01 ± 0.05 (Perry et al., 1990), and 3.24 ± 0.09 Ma (Laughlin et al., 1993), as well as an $^{40}Ar/^{39}Ar$ age of 3.64 ± 0.15 Ma (Goff et al., 2008). Basalts along the western rim of the mesa on the Grants quadrangle overlie the Grants Ridge Tuff, suggesting the older 3.7 and 3.6 Ma basalts are not present. Phenocryst content and flow breccia breaks were used in the field to split the basalts into several map units, one of which, the aphyric Ttb, appears to have a local source in the aphyric cinder cones along the eastern margin of the quadrangle. Unfortunately, poor exposure along the top of the mesa inhibits good contact control, and contacts are commonly extrapolated between sparse good exposure.

The Grants quadrangle also bears Quaternary basalts associated with the Zuni-Bandera volcanic field. Three flows are present around the town of Grants (youngest to oldest): the Paxton Springs and El Calderon flows of Maxwell (1986) and the Grants flow of Cascadden et al. (1997). The last two of these are mapped together here, however, as the Grants flow is principally distinguished by paleomagnetism and not by field criteria (Cascadden et al., 1997). The Paxton Springs flow originated from a cinder field within the Zuni Mountains, approximately 12 miles WSW of the quadrangle, and flowed down Zuni Canyon to the Grants area, while the El Calderon flow originated from El Calderon, a peak approximately 15 miles SSW of the quadrangle (Maxwell, 1986). Several attempts to date the El Calderon flow have been attempted, but the results are imprecise. Laughlin et al. (1993) obtained a K-Ar age of 54 ± 50 ka, and Champion and Lanphere (1988) obtained an age of 128 ± 33 ka. Although these ages are not close to one another, they are within error, with an average of 91 ka. Based on these ages and paleomagnetic data, however, Cascadden et al. (1997) suggest the flow erupted during the 115 to 120 ka Blake geomagnetic polarity event of Tric et al. (1991). Dunbar and Phillips (1994) obtained a Cl-36 surface exposure age of 33.4 ± 3 ka for the flow, but this appears to be too young. For the Paxton Springs flow, Dunbar and Phillips (2004) obtained a Cl-36 surface age of 20.7 ± 2.2 ka (their “Paxton Springs north”).

QUATERNARY SEDIMENTS

Quaternary sediments include fluvial terrace, alluvial fan deposits, eolian deposits, and valley floor alluvium (Figure 4-7). Quaternary deposits contain a predominance of volcanic clasts; primarily rhyolite, obsidian, basalt, and secondary Jurassic and Cretaceous limestone and sandstone clasts. Unlike the adjacent Lobo Springs Quadrangle where a sequence of fluvial terraces are preserved at varying heights above base level (Goff et al., 2008), only a single mappable terrace is preserved, an eroded remnant at a height of approximately 7m above local base level in Lobo Canyon (Figure 4). This terrace is underlain by sandy gravel with stage II carbonate development, is likely late Pleistocene in age and correlative with Qt3 in upper Lobo Canyon. The valley floor alluvium (Qal) is composed primarily of fine-grained sand, silt and clay with interbedded gravel lenses, but also includes coarse-grained gravelly terrace surfaces located within a few meters above the valley floor. Well logs from Lobo and Grants canyons indicate up to 40 m of incision below the modern valley floor, and well logs from near the Rio San Jose indicate 50 to 60 m of incision. For a more detailed discussion of the regional incisional history and development of modern drainages see Grimm (1983), Drake et al. (1991), and Goff et al. (2008).



0-0.3 m: Loose sandy gravel. 10YR 5/4 (yellowish-brown) AC horizon, structure = massive, wet consistency = sopo, texture = sand, non-effervescent in HCl.

0.3-2.3 m: Grayish-brown (10YR 5/2) silt. Well sorted, weakly consolidated, strongly effervescent in HCl. Lower section is more buff colored (10YR 6/4), moderately well sorted, coarser grained (very fine- to fine-grained), subrounded quartz-lithic sand (~20% lithics).

2.3-3.6 m: Interbedded gray silt and buff very fine- to fine-grained sandstone. Sand is light yellowish brown (10YR 6/4), weakly consolidated, moderately well sorted, subrounded to rounded, quartz lithic very fine- to fine-grained sand. Silt is gray (10YR 6/1) and weakly consolidated. Sand and silt efferevesce strongly in HCl and have pebble to cobble size clasts scattered throughout with occasional gravel lenses.

3.6-3.9 m: Well sorted, rounded, fine to medium grained quartz lithic sand with 20-30% granule to pebble gravel composed of rhyolite, obsidian, and basalt cinder clasts.

3.9-4.1 m: Light brown (7.5YR 6/3) well sorted, subangular to subrounded, very fine-grained quartz sand with 5-10% lithic grains. Non-effervescent in HCl. Low angle planar cross-beds throughout interval; eolian deposit.

4.1-4.7 m: Sandy clast-supported, well-imbricated, pebble (predominant) to cobble gravel with clasts of rhyolite, obsidian, minor baslt, and rare siltstone and sandstone (reworked Jurassic and/or Cretaceous clasts). Non-effervescent in HCl

4.7-5.0 m: Dark brown (10YR 3/3), poorly sorted, subangular, fine-grained, quartz-lithic sand with abundant clay (clayey sand). Non-effervescent in HCl.

5.0-5.7+ m: Weakly imbricated, clast-supported, pebble to cobble gravel with clasts of rhyolite, basalt, minor andesite and chert.

Figure 4. Qal stratigraphy in Lobo Canyon.

Eolian deposits include young sand sheets and dunes in valleys and older sand sheets on mesa tops (Figure 5, 6). Valley floors in Lobo and Grants canyons are locally mantled by eolian deposits (Qes2), including sand sheets and stabilized dunes. These include late Holocene and modern deposits. Locally, buried soils with Stage I-II carbonate are preserved indicating the presence of buried discontinuous late Pleistocene eolian deposits. A sand sheet is also present is some areas on Horace Mesa (Qes1). The Horace Mesa sand sheet comprises a middle Pleistocene eolian deposit with Stage II-III carbonate approximately 1 m thick where not eroded, overlain by a thin (20-30 cm) late Holocene eolian deposit (Figure 7).

Top photo shows lack of soil development in upper portion of deposit. Photo location: 246740 m E, 3902156 m N, UTM zone 13, NAD 1983

Bottom photo shows upper reddish eolian deposit (0-1.7m) overlying tan eolian deposit with low angle planar cross beds (to right of rock hammer). Buried soil with Stage I carbonate is present in auger hole at base of outcrop. Photo location: 245206 m E, 3903979 m N, UTM zone 13, NAD 1983.

Figure 5. Qes2 deposits in Lobo Canyon.

Figure 6. Qes1 sand sheet on Horace Mesa (photo taken on Lobo Springs Quadrangle).

Fan complexes deposited by small drainages are located at the base of Grants Ridge and Horace Mesa. Older (middle(?) Pleistocene) fans (Qfo) graded to a base level approximately 10 m above the modern valley floor form a complex on the north side of East Grants Ridge near the eastern Quadrangle boundary. Younger (middle to late Holocene) fans (Qfy) emanate from small drainages near the base of Horace Mesa and on both sides of Grants Ridge (Figure 7). Young fans are graded to the modern valley floor and merge with Qal.

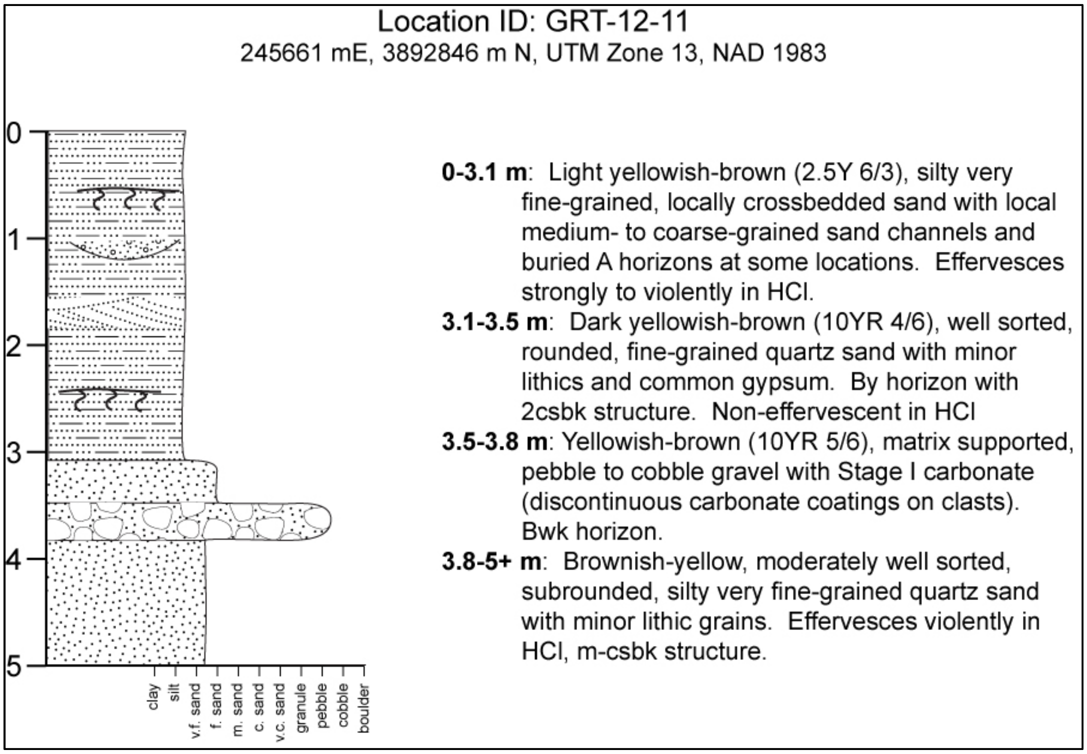


Figure 7. Qfy stratigraphy near base of Horace Mesa.

A tufa mound which caps a small Chinle erosional remnant forms an isolated outcrop within the Paxton Springs flow in the southwest corner of the Quadrangle (Figure 8). The tufa contains casts of grasses, reeds, and other plant matter The mound is elongated in a general north-south orientation, stands approximately 16 m above the surrounding valley floor, and is estimated to be middle to late Pleistocene in age.

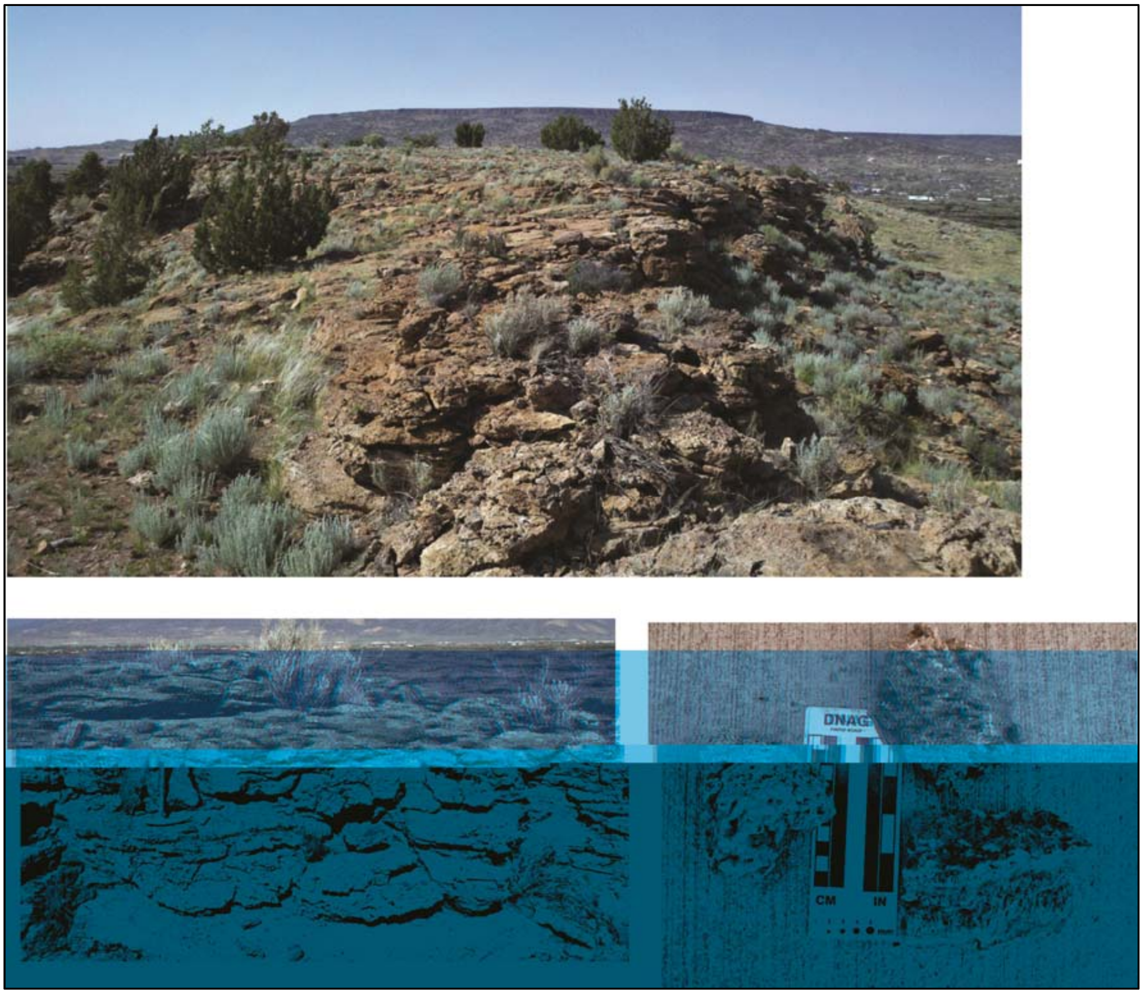


Figure 5. Photos showing tufa mound (top), 246740 m E, 3902156 m N, UTM zone 13, NAD 1983 (southwest corner of Grants Quad), outcrop detail (lower left), closeup showing grass, reed, and other plant casts (lower right).

STRUCTURE

Grants quadrangle is located on the southeast edge of the San Juan Basin and on the western limb of the north-east trending McCarty syncline (Hunt, 1938). Two to three sub-parallel faults trend northeast to southwest across the quadrangle and offset Upper Triassic strata against Upper Cretaceous strata with an estimated throw of 850 feet (termed the San Rafael fault by Kerr and Wilcox, 1963). These faults splay towards the northeast, and are responsible for the topographic features of Black Mesa/West Grants Ridge, Grants Ridge and East Grants Ridge. Each fault or splay sets older Mesozoic strata against younger Mesozoic strata with the oldest strata to the west and successively younger strata to the east. The majority of the faults do not offset the younger volcanic rocks, except for one strand that does offset the basalt capping Grants Ridge (Thaden et al., 1967).

Two faults offset young volcanic rocks on Horace Mesa, and are northeast-southwest to north-south trending. In addition, outcrops of Upper Cretaceous Dakota Sandstone are tilted to the east in an arcuate monocline that trends north-south, but is truncated by the San Rafael fault. The monocline does not appear to affect the overlying younger volcanic rocks and is probably Laramide in age.

UNIT DESCRIPTIONS

Quaternary

Qal **Alluvium—**Deposits of sand, gravel and silt in main valley bottoms; predominantly Late Holocene in age where exposed. Maximum thickness of various alluvial deposits is uncertain but is at least 40 m. Well logs from sections 26 and 35, T 12 N, R 10 W (in western Lobo Canyon) indicate a total thickness of 20 to 40 meters of alluvium overlying Chinle Formation shale. Well logs from the NW¼, Section 20, T 11 N, R 9 W (in western Grants Canyon) indicate a total thickness of around 40 meters of alluvium overlying red clay and shale. Well logs from Section 6, T 10 N, R 9 W (Rio San Jose valley) indicate a total thickness of 50 to 60 meters of alluvium and interbedded basalt overlying red shale (Chinle Formation). Alluvium is typically fine-grained, silt and sand dominated deposits with pebble and cobble-gravel lenses and interbedded gravel beds (Figure 4). Clasts in gravel lenses from locally derived sources in Lobo and Grants canyon valley floor alluvium. Includes some low (<3m above modern valley floor) alluvial surfaces of possible middle Holocene age. Deposits are characterized by weakly-developed soils with 10YR-7.5YR color (reflecting varying parent material), none to Stage I carbonate morphology, and lack of Bt horizon development (Table 1). Locally includes thin eolian mantle <50 cm thick.

Qsw Colluvial, eolian, and alluvial deposits that have accumulated behind large landslide blocks forming distinctive benches.

Qt **Alluvium underlying terrace surfaces—**Deposits of sandy pebble to cobble size gravel underlying terrace surfaces located approximately 7 m above local base level in Lobo Canyon. Clasts are subangular to rounded rhyolite, obsidian, basalt, limestone, sandstone, andesite, chert, and minor granite. Typically forms fill terraces with deposit thickness greater than 7 m. Deposits are characterized by stage II carbonate, Bt horizon is typically absent (stripped?) (Table 1). Likely late Pleistocene in age and correlative with Qt3 in upper Lobo Canyon in Lobo Springs Quadrangle (Goff et al., 2008).

Qfy **Young Alluvial fans—**Typically fan-shaped deposits sand, silt, and clay with pebble-and cobble size gravel lenses deposited at the mouth of small drainages at the base of Grants Ridge and Horace Mesa; associated with present drainages and usually not incised more than a few meters; grades into alluvial deposits along main channels. Deposits are characterized by weakly-developed soils with 7.5YR – 2.5Y color (reflecting varying parent material), none to Stage I carbonate morphology, local gypsum accumulation, and lack of Bt horizon development (Figure 7; Table 1). Deposits are middle to late Holocene age; maximum exposed thickness about 5 m.

Qfo **Older Alluvial fans—**Dissected remnants of fan-shaped deposits of coarse to fine gravel and sand, silt, and clay graded to a base level 10 m or more above the modern valley floor; Middle(?) Pleistocene age. Forms a fan complex on the north side of East Grants Ridge. Characterized by well-developed soils with stage III carbonate morphology and Bt horizon development (Grimm, 1983). Approximate thickness about 5 to 10 m or more.

Qes2 **Eolian deposits in Lobo and Grants Canyons—**0.5 to 10 m or more thick deposit of well-sorted, subrounded, very fine- to fine-grained quartz lithic sand forming sand sheets in Lobo and Grants Canyons. Distinguished by lack of soil-profile development, although locally includes buried soils with Stage I-II carbonate morphology (Table 1). Color of deposits typically ranges from 5YR to 7.5YR, reflecting varying source areas for different eolian events; low-angle planer cross bedding locally preserved (Figure 5).

Qed **Dune sand—** well-sorted, subrounded, very fine- to fine-grained quartz lithic sand forming stabilized dunes in Lobo Canyon. Distinguished by lack of soil-profile development. Qed in Grants Canyon appears destabilized due to anthropogenic activities.

Qes1 Older Eolian deposits of Horace Mesa—0.2 to approximately 1 m thick deposit of silt and very fine sand forming sand sheet on Horace Mesa (Figure 6). Characterized by thin (<10 to 30 cm thick) late Holocene deposit overlying discontinuous, buried middle to late Pleistocene eolian deposit approximately 1 m thick. Surficial soil is weakly developed with 10YR color, none to Stage I- carbonate morphology, and lack of Bt horizon development. Buried soil is well developed, with Stage II+ to III carbonate morphology, Bt horizon with 5YR to 7.5YR color. Deposit locally includes scattered large basalt clasts - Qc derived from basalt at top of nearby scarp.

Qls Landslides—Poorly sorted debris that has moved chaotically down steep slopes; slumps or block slides (toreva blocks) partially to completely intact, that have moved down slope; slumps and block slides usually display some rotation relative to their failure plane; thickness varies considerably depending on the size and nature of the landslide.

Qlt Calcareous Tufa—Porous limestone with casts of grasses, reeds, and other plant matter, bedded on a 1 cm to > 10 cm scale with a 30-40 cm layer of plant casts near top (Figure 8). Weathered surface is pale yellow to light yellowish brown, fresh surface is light gray with yellowish brown bands of plant mats and dark gray manganese-stained layers. Distinctive egg shell weathering on exposed surfaces. Maximum thickness approximately 7 m.

Qc Colluvium, undivided—Very poorly sorted gravels and sands deposits on steep slopes. Mapped where colluvium obscures underlying geologic relationships. <1 to 4 m thick.

Qoa Older alluvium, undivided—High-level sands with rare pebbles of exotic(?) clasts. ‘Exotic’ clasts consist of white to pink quartzite and very dark gray chert; the former is found as xenoliths in nearby cinder deposits, however, and could be locally derived. The later has not been seen as xenoliths. No exposure of the soil developed in this alluvium has yet been found. Unit is 1-3 m thick.

Qbp Paxton Springs flow—Younger Quaternary basalt flow. Dark gray to black basalts largely uncovered by eolian material. Thin sections show olivine and rare pyroxene and plagioclase phenocrysts in a groundmass of plagioclase, pyroxene, and opaque oxides (Maxwell, 1986). Originated in the Zuni Mountains, 12 miles to the WSW. Cl-36 surface exposure age of 20.7 ± 2.2 ka (Dunbar and Phillips, 2004).

Qbc El Calderon flow—Older Quaternary basalt flows. Black basalts that are, significantly buried by eolian material. Thin sections show olivine phenocrysts in a groundmass of plagioclase, clinopyroxene, olivine, and opaque oxides, with rare glass (Maxwell, 1986). Includes the less extensive, older Grants flow of Cascadden et al. (1997). Originated from El Calderon, a peak 15 miles to the SSW. Exact age uncertain (see report), but constrained to upper Pleistocene, 50-130 ka.

Tertiary

Pliocene Volcanics

Ttb, Ttc, Ttcr Aphyric trachybasalt—Very dark gray, very sparsely (<<1%) porphyritic flows. Phenocrysts consist of fine olivine, plagioclase, and possibly pyroxene. Associated cinder deposits are **Ttc** and **Ttcr**, the former being light to dark brown and the later being distinctly deep red in color. Cinder deposits contain rare xenoliths of Mesozoic sandstone as well as white to pink quartzite. Appears to overlie **Ttmb** and **Ttmpb**, but the relationship is not clearly expressed in outcrop.

Ttsb Spotted trachybasalt—Very dark gray, very sparsely (<<1%) porphyritic, 'spotted' flows. 'Spotting' consists of conspicuous abundant white to very light gray spots 2-4 mm across. Phenocrysts, where present, consist of plagioclase and olivine. No associated cinder has been found.

Ttmb, Ttmc Older sparsely megacrystic trachybasalt—Very dark gray porphyritic flows with sparse megacrysts. Megacrysts consist dominantly of pyroxene but are rarely of plagioclase, and are 1-2 cm across. In addition, flows consist of 4-10% medium phenocrysts of pyroxene (2-5%, up to 4mm across, generally anhedral), plagioclase (<1 to 1%, up to 4mm across, generally anhedral), and sparse olivine (<1%, up to 1 mm across, anhedral and commonly replaced by iddingsite). Associated cinder deposits are mapped as **Ttmc**. Unit appears to overlie **Ttmpb**, but the relationship is not clearly expressed.

Ttmb2 Younger sparsely megacrystic trachybasalt—Very dark gray porphyritic flows with sparse megacrysts locally found above the scoriaceous top of **Ttmb**. Similar in appearance to **Ttmb**, save for rarer and possibly smaller megacrysts, it is distinguished from **Ttmb** by the presence of a broad scoriaceous zone found toward the top of the main **Ttmb** cliff, separating the younger and older flows. Overlies **Ttmb**.

Ttmpb Sparsely megacrystic, sparely phenocrystic trachybasalt—Very dark gray sparsely porphyritic flows with very sparse megacrysts. Megacrysts are dominantly of pyroxene by with rare plagioclase, both of which are 1 to 1.5 cm across. Medium phenocrysts constitute generally <1%, but locally up to 5%, of the flows, and are also dominantly pyroxene but locally include plagioclase; each is up to 3 mm across and anhedral.

Ttma Abundantly megacrystic trachyandesite—Very dark gray megacryst-rich flows. Megacrysts are dominantly plagioclase, with rare pyroxene, that are up to 1 cm across and constitute 5-10% of the flows. Unit may be a local plagioclase-rich zone of unit **Ttmpb**, or may be a separate flow underlying **Ttmpb**.

Ttba, Ttbac Sparsely megacrystic, porphyritic basaltic trachyandesite—Medium to very dark gray porphyritic flows with sparse megacrysts. Macroscopic phenocrysts are dominantly plagioclase (5-15%, up to 6 mm across, subhedral to euhedral, white to clear), followed by pyroxene (<1-10%, up to 8 mm across, anhedral to subhedral, generally black but variably degraded to reddish and orangish minerals). Sparse (<<1 to <1%) megacrysts of pyroxene are up to 1.5 cm across and anhedral. Associated cinder is mapped as **Ttbac**. On the east side of East Grants Ridge, basalt bands thin rapidly from the north and south edges of the Ridge toward the center, suggesting the basalt onlapped a topographically high **Tgro** ridge or dome. On the west side of the Ridge, the basalt cliffs drop in elevation along a north-striking monocline-like trend, possibly draping over a paleoslope. A thick mass of basalt surrounded by cinder above the perlite mine at 0248140mE, 3899360mN (NAD27, Zone 13S) may be an intrusive plug (Thaden et al., 1967) or a lava pond at the center of the cinder cone that solidified in place (Crumpler, 2003). The shallow valley in the cinder cone to the north of the mass of basalt may be the location that the basaltic magma breached the cone and flooded northward and westward to cap the Grants

Ridge mesas (Crumpler, 2003). Overlies **Ttci**, **Ttbb**, **Tgro**, **Tgrt** and a variety of Mesozoic rocks. Up to about 100 m thick by the perlite mine, up to 30 m thick outside the source cone.

Ttcu **Trachybasaltic cinder, undivided**—Cinder deposits with no clear equivalent basalt. Light to dark brown to reddish brown, vesicular trachybasaltic cinder.

Ttci **Inset trachybasaltic cinder—**Cinder deposits clearly inset upon Mesozoic strata at the west end of East Grants Ridge. Light brown to reddish brown to dark red blocks of moderately to strongly vesicular, aphyric basaltic scoria with a cement of sparry calcite. Generally poorly exposed, and surrounded mainly by colluvium. Overlies or intrudes Mesozoic strata, underlies **Ttba**. At least 30 m thick.

Ttbb **Trachybasaltic breccia**—Dark gray to dark brownish gray flow breccia with local, discontinuous, aphyric flow core, forming a distinct bed inset upon Mesozoic strata on the West end of East Grants Ridge. Basalt blocks and flow core bear sparse, indistinct phenocrysts that are likely small plagioclase, and amorphous clots of orangish brown Fe-oxide that may be degraded pyroxene. Weathered surfaces bear common, vague to distinct, light gray spotting, with spots typically 1 cm across. Bed trends from moderately west-dipping at west end, to subhorizontal, to moderately east-dipping at east end, with the east end clearly inset upon Mesozoic strata. Intercalates with **Ttci**, underlies **Ttba**. 5-10 m thick.

Ttpb **Porphyritic trachybasalt—**Very dark gray porphyritic basalt with distinct greenish alteration. Phenocrysts are dominantly of pyroxene (5-10%, 0.1 to 1.3 cm across, subhedral to euhedral), with lesser plagioclase (1-3%, up to 0.5 cm across, subhedral), and both phenocryst types are variably degraded. Greenish alteration consists of an abundant greenish brown to greenish gray stain seen on weathered and fresh faces. **Ttpb** is only very locally exposed inset upon Mesozoic strata at the west end of East Grants Ridge, and is possibly intrusive. At least 1 m thick.

Tgro **Rhyolite of Grants Ridge—**White to medium gray to brown, sparsely porphyritic lavas and local breccias. Phenocrysts consist of potassium feldspar, plagioclase, and very rare quartz.

Massive to strongly flow-foliated, with bands of coarse vesicles and local lithophysae following foliation trends. Vesicles are uncommonly rimmed in fine crystals. Some areas, particularly along the north flank, are rich in nodules of obsidian. A strongly flow-foliated vitrophyre is common to the base of the dome at least along the north flank, with steep southward dips to the foliation suggesting the rhyolite is somewhat inset upon the underlying tuff. Small exposures of pumiceous clastic rocks suggest that minor tephra beds intercalate with the rhyolite lavas. Overlain by **Ttba** and **Ttbac**, underlain by **Tgrt**. Dated by the K-Ar method at 3.34 ± 0.16 Ma from an unknown location (Lipman and Mehnert, 1979). At least 180 m thick.

Tgrt Grants Ridge Tuff—White to light gray to pale red ignimbrite, fallout, flow, surge, and breccia deposits with local alluvial reworking, particularly at the top. Highly variable, but typically consists of a coarse, lithic-rich basal zone, and fine-grained, pumice-rich upper zone, and capped by alluvial gravels. Lithics are of rhyolite, granite, gneiss, chert, sandstone, limestone, and basanite (Goff et al., 2008). Keating and Valentine (1998) identified two eruptive sequences of ignimbrites overlain by fallout and surge beds. Alluvial beds consist of moderately to poorly sorted pebbles and sparse cobbles of angular to subangular aphyric gray rhyolite and/or subrounded to rounded obsidian with sparse granite and quartz-rich sandstone gravels. Alluvial beds are commonly thinly cross-bedded, and occur in thin to medium (10 cm to 1 m thick), locally channel-shaped beds. Goff et al. (2008) dated obsidian clasts from upper tuff beds beneath Mesa La Jara by the $^{40}Ar/^{39}Ar$ method at 3.26 ± 0.04 Ma. Thickness trends suggest the source lay beneath the rhyolite of Grants Ridge. At least 150 m thick.

Pliocene Sediments

Tvss Sandstones interbedded with trachybasalts—Light gray sandstones and basalt-bearing pebbly sandstones. Only locally preserved between basalt flows. Thinly bedded with poorly sorted sands and rare fine subrounded pebbles of trachybasalt. Very poorly exposed.

Tvsb Basaltic-rich volcaniclastic gravels—Gray to tan alluvial deposits of subrounded to rounded trachybasaltic pebbles and cobbles. Interbeds with trachybasalt flows to the east on the Lobo Springs quadrangle (Goff et al., 2008).

Tvsd Coarse basalt-dominated debris flow deposits—Very poorly sorted pebbles to local boulders of angular to subrounded basalts of various textures. Deposits are massive and clast-supported with only minor matrix material between clasts. Only locally exposed at the very NW corner of Horace Mesa, where it underlies **Ttmpb** with a very irregular upper contact; basal contact is not exposed.

Cretaceous

Crevasse Canyon Formation

Kcg Gibson Coal Member—Interbedded black and brown siltstone, thin to medium bedded tan to greenish gray sandstone, and black coal. Sandstones are well to moderately sorted, very fine to medium grained, with angular to subround quartz. Composition is 90% quartz, 10% lithics with less than 1% clay matrix (litharenite). Sandstone beds are cross-bedded with a range from trough cross-beds to large-scale, low-amplitude planar cross-beds. Locally, ripple marks are preserved. Elliptical to spherical siderite to goethite concretions are common as is petrified wood. Coal beds are generally <0.5 m thick. Lower contact is gradational with underlying Dalton Sandstone, top is overlain by Tba of Horace Mesa. Maximum exposed thickness is approximately 350 m.

Kcda Dalton Sandstone Member—Forms stepped cliff with lower yellow-orange cliff, intervening short slope and upper white cliff. Lower sandstone has thin beds with abundant pelecypod casts and molds and is carbonate cemented. This sandstone is well sorted, very fine grained with angular quartz grains. Composition is 95% quartz, 5% lithics with less than 1% clay matrix (sublitharenite). Upper sandstone is weakly cemented and is well sorted, fine grained with angular to subround quartz grains. Composition is 90% quartz, 10% feldspar and <1% lithics. Upper and lower contacts are gradational and maximum exposed thickness is <25 m.

Kcmm Mulatto Tongue, Mancos Shale—Distinctive mustard yellow shale that coarsens upwards into laminated siltstone. Siltstone is bioturbated and locally can contain pelecypod shells. Upper and lower contacts are gradational. Up to 240’ thick.

Kcs Stray Sandstone Member—Forms stepped cliff with two prominent red-orange cliffs separated with a short slope. Sandstones are medium bedded with planar cross-beds and are white to yellowish gray on fresh surfaces. Well to moderately sorted, very fine to medium grained with angular quartz grains. Composition is 99% quartz, 1 % lithics with <1% clay matrix (quartz arenite). Topmost 1 m of sandstone is a pebble to cobble conglomerate with clasts of quartzite, chert and quartz. Upper and lower contacts are gradational and maximum exposed thickness is <40 m.

Kcdi Dilco Coal Member—Interbedded black to brown siltstone, thin to medium bedded tan to olive green sandstone and black coal. Sandstones are well to moderately sorted, very fine to fine grained with angular quartz grains. Composition is 90% quartz, 10% lithics (including up to 5% muscovite) with up to 5% potassium feldspar altered to clay as a matrix. Sandstones are cross-bedded to ripple laminated. Elliptical to spherical siderite to goethite concretions are present throughout the unit. Upper and lower contacts are gradational and maximum exposed thickness is <150 m.

Gallup Sandstone

Kgm Main Body—Yellowish gray to white, medium to thick bedded sandstone. Moderately sorted, fine to very fine grained with angular to subrounded quartz grains. 95% quartz, 5% lithics (including muscovite mica) as well as plant debris. Contains up to 30% clay matrix from altered feldspar (quartz wacke). Often, beds are bioturbated with ~1.0 cm diameter cylindrical, vertically oriented burrows. Carbonaceous shale locally intercalated with sandstone. Faint, very low angle trough cross beds occur in sets less than 0.25 m thick, with paleocurrent azimuth of 010°. Beds primarily planar-tabular or laminated. Lower contact gradational with Mancos Shale unit and maximum exposed thickness with <25 m.

Kgu Upper Tongue—White, medium bedded sandstone locally capped by well-cemented, fractured, brown-weathered, planar cross-bedded sandstone. Brown sandstone is carbonate sandstone, underlying white sandstone is not. Sandstones are well-sorted, fine grained with angular quartz grains. Composition 95% quartz and 5% lithics with 15 to 25% clay matrix (quartz wacke). White sandstone has no muscovite, overlying brown sandstone has trace amounts of both muscovite and biotite. Trough crossbeds occurs in sets less than 0.5 m thick with paleocurrent azimuths of 025°. Cross beds are somewhat steeper than in lower tongue. Local internal scour surfaces present, as well as hematitic concretions and stained surfaces. Upper and lower contacts with Mancos Shale are gradational and maximum exposed thickness is <30 m.

Kgl **Lower Tongue—**White, medium bedded sandstone capped with brown-weathered sandstone as in Kgu. Sandstone well to moderately sorted, fine to very fine grained with angular quartz grains. Composition is 95% quartz and 5% lithics with 10 to 15% clay matrix (quartz arenite). White sandstone contains no mica, but overlying brown sandstone contains traces of muscovite. Cross bed sets are 0.5 m thick, are low angle trough cross beds and have paleocurrent azimuths of 150°. Top of unit locally conglomeratic with sandstone clasts and rare shark teeth. Upper and lower contacts with Mancos Shale are gradational and maximum exposed thickness is <15 m.

Jurassic

Jm **Morrison Formation, undivided—**Interbedded sandstone and shale. Includes Jackpile Member, Brushy Basin Member, Salt Wash Member, Recapture Member and Bluff Sandstone (Lucas and Zeigler, 2003). Combined thickness is on the order of 200 m.

Js **Summerville Formation—**White, red-brown and light brown fine to very fine muddy sandstone interbedded with brown mudstone and siltstone. Up to 40 m thick (Thaden et al., 1967).

Jt **Todilto Formation—**Pale gray to pale yellow micrite. Thick bedded and coarsely crystalline in upper part, crinkly bedded in middle part and laminated at base. Up to 12 m thick (Thaden et al., 1967).

Je **Entrada Sandstone—**Yellow fine to medium grained quartz arenite with large scale eolian crossbeds. Up to 40 m thick.

Triassic

TrC Chinle Group undivided – Red and purple mudstones, siltstones and fine to medium grained sandstones. Mudstones and siltstones commonly included pale green reduction spots up to 2 cm in diameter and small lenses of calcrete granules to pebbles. Sandstones are grayish purple lithic wackes with grains of mudstone, chert, micrite and quartz that are moderately sorted and subround. Sedimentary structures include crossbeds, crosslaminations and localized soft sediment deformation and bioturbation. Sandstones also may include small lenses of clast-supported rip-up clast conglomerate with clasts that are purple-brown mudstone and siltstone. Exposures of Chinle Group strata occur only as dislocated blocks within landslide deposits, such that thickness is unknown

Permian

Ps San Andres Formation – Pale gray to buff dolomitized limestone that occurs only in the southwest corner of the map. Tabular to wavy, thinly bedded, and includes abundant and large pieces of gray and white banded chert. No fossils observed. Probably correlative with the Bonney Canyon Member of the San Andres Formation to the south due to presence of distinctive banded chert. Maximum exposed thickness is <10 m.

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