Geologic Map of the Black Butte 7.5-Minute Quadrangle, Socorro and Valencia Counties, New Mexico

By
Alex J. Rinehart[1], David W. Love[2], and Phil L. Miller[2]

[1]*Earth and Environmental Science Department,*
New Mexico Institute of Mining and Technology, Socorro, NM 87801

[2]*New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801*

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New Mexico Bureau of Geology and Mineral Resources
801 Leroy Place, Socorro, New Mexico, 87801-4796

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Summary

The Black Butte 7.5-minute quadrangle extends from the eastern margin of the Rio Grande valley across low-relief uplands toward Abo Canyon and the northern Los Pinos Mountains to the east-southeast. The area is in the southeastern part of the extensional Albuquerque Basin of the Rio Grande rift. Black Butte, also known as Turututu, is the most prominent feature on the quadrangle with a summit elevation of 1,670 m (5,478 ft). The lowest part of the quadrangle is slightly less than 1,475 m (4,840 ft) in an unnamed tributary to the Rio Grande valley on the west edge of the quadrangle. The area is primarily semiarid grassland with the northern edges of the Chihuahuan desert along its southern margin and on rockier south-facing slopes.

The quadrangle is crossed from southeast to northwest by three named valleys and other unnamed drainages from Abo Wash in the north, Pino Draw in the south-center, and Maes Arroyo in the southwest. Because three unnamed drainages are important in describing local deposits related to the geologic development of the landscape, we name them for local features or nearby roads already on maps. Tururtutu Draw drains the area on the south side of Black Butte, runs west and west-northwest and joins the Rio Grande valley north of Boys Ranch on the adjacent Abeytas quadrangle. Isabel Draw drains an area south of the Abo drainage, runs west to the Rio Grande valley, and is named for east-west Isabel Road, which crosses the drainage repeatedly. Similarly Amizette Draw (east of Vargas on the map) has headwaters between Isabel Draw and Pino Draw and drains an eroded valley from the higher inset fan remnants on the east side of the quadrangle to flats in the central part of the quadrangle.

Black Butte and two small exposures to the west are the only outcrops of non-Quaternary rocks on the quadrangle. They consist of Oligocene-lower Miocene lava flows of dark basaltic andesite underlain by three ash-flow tuffs from three calderas to the southwest.

Quaternary surficial sediments with distinctive suites of clast compositions are (1) fluvial ancestral Rio Grande pebbly sands, sandstones, and gravels from the north; (2) broad constructional and inset fans of the large Abo drainage from the east; (3) broad constructional fans from the Palo Duro drainage from the south-southeast; (4) inset fans of Pino Draw from headwaters in Los Pinos Mountains to the east-southeast; and (5) smaller alluvial fans and inset fans from Los Pinos Mountains. Turututu, Amizette, Isabel and smaller drainages rework sediments from these sources to develop inset terraces, slopes, swales, valley floors, modern channels, and alluvial fans. Alluvial fans and inset fans from the Abo drainage dominate most deposition in the eastern half of the quadrangle, and along the northern part parallel to the present Abo valley. Past paths of Abo fans are indicated by several inset levels of alluvial plains and fan segments. Palo Duro fans dominate the southwestern part of the quadrangle and smaller fans dominate the southeastern corner. Rio Grande pebbly sand covers nearly horizontal steps and slopes on the west and west-central parts of the quadrangle.

The Santa Fe Group of basin fill within the Rio Grande rift is considered to be all deposits underneath the maximum level of fill before the Rio Grande began to dissect its valley about 800,000 ka (Connell et al. 2013). Therefore, the highest levels of Rio Grande deposits and the piedmont alluvium interfingering, below, and forming bluffs to the east of the fluvial deposits are considered to be Quaternary upper Santa Fe Group. The alluvial units that crosscut or bury the top of the fluvial deposits are considered to be post-Santa Fe Group.

Although differences were delineated between alluvial deposits based on presence and absence of somewhat diagnostic clasts, the tops and gentle slopes of most of the older deposits have developed very similar soils with pedogenic calcium-carbonate horizons reaching stages III to V of Machette (1985; Birkeland, 1999). Other soils appear to have been stripped, so that some deposits appear to be younger than they would be if their surfaces had remained stable.

Subtle north-northeast-trending topographic steps from Maes Arroyo to Abo Arroyo indicate Quaternary fault scarps, but they are eroded extensively with laid-back gentle slopes. These slopes are developed on unconsolidated ancestral Rio Grande sediments and poorly consolidated piedmont-basin fill related to older fan deposits. Three strands within the Maes-Abo fault zone of normal faults step planar levels of ancestral Rio Grande deposits down to the west across the southwest-west-central part of the quadrangle. The most prominent normal-fault trace, the Military Road fault zone, is down-to-the-east with a young-looking graben at the base in slope. The narrow graben also deforms an intermediate terrace of Abo valley.

Black Butte is cut by this fault zone on its east side and a buried fault on its west side. The butte is uplifted approximately 85 m relative to exposures of the same volcanic sequence 1 km to the west, and correlative rocks penetrated in a well northeast of Black Butte are 155 m below the surface (B. Black, personal commun. 2014).

Both Bouguer and isostatic gravity anomalies in the area between the rift-flanking uplifts to the east and the Rio Grande valley to the west have a gradient sloping down to the northwest with a gravity high protruding north-northeast coincident with the Military Road fault zone. All modern stream valleys in and immediately surrounding Black Butte quadrangle descend nearly perpendicular to the gravity anomaly contours of Gillespie et al. (2004) and Grauch et al. (2013). The stream paths trend perpendicular to both ascending and descending gravity anomaly contours. Relatively small variations in the anomaly contours appear to correlate with changes in stream direction, including a pronounced bend from the west-directed to northwest-directed course of the lower Abo valley at a small gravity anomaly 'depression' immediately east of the Military Road fault zone. The sensitivity of modern drainage flow directions to small gravity anomalies argues for recent tectonic deformation.

Deposits of the Rio Grande

The Rio Grande suite of cobbles and pebbles consists of well-rounded, extra-basinal, hard rocks from northern New Mexico such as multi-colored quartzites, multi-colored cherts, volcanic rocks such as basalt, ash-flow tuffs, andesites and dacites, pumices, and Rabbit Mountain obsidian (1.44 Ma; Kelley et al. 2013). Low in the section of Rio Grande deposits on the western side of the quadrangle (elevation 1,500 m) are pumice-raft deposits, cross-bedded pumice granules, and individual pebbles of pumice all chemically similar to the Guaje pumice eruption at the base of the Otowi Member of the Lower Bandelier tuff (N. Dunbar and L. Heizler, written commun., 2014; 1.61-1.66 Ma; Kelley et al., 2013). The maximum eastern and highest extent of ancestral Rio Grande deposits runs generally north-south from Abo valley to Black Butte and southwest from there to the southwest corner of the quadrangle. The high topographic level (1,558 m elevation), presence of Rabbit Mountain obsidian, and perhaps clasts of upper Bandelier tuff (1.25 Ma) indicate that this level of deposits is near the top of aggradation at roughly 800 ka (Connell et al. 2013). Other aggradational, erosional, and structural features can be related to this relative time marker.

Three other time markers related to Rio Grande deposits from adjacent quadrangles may be used to estimate relative timing of episodes of aggradation, erosion, and deformation. These markers are three river terraces along the eastern margin of the Rio Grande valley. These terraces are described by McCraw et al. (2006) and Connell et al. (2007). The highest terrace in Albuquerque contains Lava Creek B ash (640 ka) at an elevation of 55-75 m above the Rio Grande floodplain. A similar terrace correlated to the one in Albuquerque is slightly lower in the adjacent Abeytas quadrangle at 50-65 m above the floodplain. The overlying sediments from an inset Abo fan must be younger than the ash. A terrace with a tread 27-30 m above the Rio Grande floodplain has basalt flows within (156 ka) and on top of (100 ka) the terrace (Connell et al., 2007), and a ^{36}Cl age estimate of 122 ka near Socorro (Phillips et al. 2003). Near the mouth of Abo valley, in the northwest corner of the Black Butte quadrangle, this Rio Grande terrace tread is also overlain by fan deposits from Abo drainage.

Deposits related to the Abo drainage

Several broad levels of fans and inset fans related to the course of the Abo drainage crossed the eastern side of the quadrangle prior to the incision of the Abo valley. The suite of clasts from the Abo drainage include pebbles, cobbles, and even boulders of limestone, slabby red sandstone, and Proterozoic gray quartzite, metavolcanic rocks, gneissic schists, bull quartz and granite. Chert pebbles are present, but uncommon. The three highest and oldest are delineated by units Qabd, Qafo1, and Qafo2 on the map of the Black Butte quadrangle. On the north side of Abo valley is the "Dairy" surface beneath and surrounding the artificial fill. A similar surface south of the Abo valley is the "Comales" surface on the map. These levels appear to pre-date the maximum level of the Rio Grande and may grade downward into more generalized piedmont basin fill (QTsps). Two levels of inset fans below the highest surfaces south of Abo valley were developed in the east-central map area and are labeled as "Cuchilla" (higher) and "Cabresto" (lower), underlain by units Qafbs and Qaftt. These deposits have uncertain connections to Abo headwaters to the east. They are offset different amounts by the Military Road fault zone.

West of the Military Road fault zone, and younger than the age of maximum aggradation of Rio Grande deposits, the Abo drainage established a number of courses across the area before entrenching its valley in its present location. Remnants of the early inset fans exist on both sides of the valley, but at least two levels on the north side of the valley may have been deposited from a more northwesterly path of the Abo drainage. Several inset paths are partially preserved as terrace and valley-mouth fans on the south side of Abo valley and now are eroded to form east-west divides between Abo valley and Isabel Draw. Although three down-to-the-west normal faults or fault zones step the Rio Grande deposits down to the northwest, most of the inset Abo fans are minimally cut by the faults. The younger Abo fan remnants step farther and farther west through time, probably reflecting incision of the Rio Grande valley and aggradation of different lobes of Abo fans.

Lower along the margins of Abo valley are two pairs of two closely spaced terraces, the treads of which are from 17-20 m and 10-12 m above the valley floor. These terraces may be traced downstream to broad, uncontained fans that bury terraces of the Rio Grande. Within Abo valley, historic 20th century incision has abandoned the floodplain and valley floor to form a terrace 4-5 m above the current channel.

Playas, or "floodplain playas" of Peterson (1981), developed at different times in the past, primarily from fault offset and perhaps from deflation. In many cases, although the landform is old, the deposits in the bottom are recent. The older playas, developed on older alluvium are designated Qplo. The more recent ones, with young sediment, are designated Qpl.

Deposits of Pino and Turututu Draws

After one of the older inset paths of Abo drainage created a broad fan trending southwest toward Black Butte from a natural diversion across the south side of Abo drainage 7 km upstream, Pino Draw from Los Pinos Mountains to the southeast developed its course along the southern margin of that Abo fan and created distinct inset terraces along its present course and around the south side of Black Butte adjacent to the northern edge of the Palo Duro fan. After Pino Draw established and entrenched its present course on the north side of Black Butte, Turututu Draw developed below the older Pino inset fan on the south side of the butte and was joined by distal-fan drainages from the southeast. A suite of limited relief (< 1-m) terraces upstream from the Military Road fault zone may be related to the uplift and subsequent downcutting of Pino Draw across the fault zone. Higher relief inset terraces downstream of the Military Road fault zone are presumed to be related to the aggradation and downcutting of the Rio Grande valley. One of the most extensive levels of inset terraces are fan deposits debouching onto a terrace of the Rio Grande approximately 50 m above the Rio Grande valley. These fans correspond to a very extensive terrace along the Abo drainage (inset upstream; broad, uncontained fan downstream).

Deposits of Palo Duro and Los Pinos fans from the south-southeast

A large fan from the Palo Duro drainage to the southeast extends north-northwest; deposits from this fan interfinger with ancestral Rio Grande gravelly sands at a level of approximately 1,555 m. Subtle inset terraces along the Palo Duro fan were noted, but not mapped separately across the fan surface. The Palo Duro fan is composed of a suite of limestone, red sandstone, Proterozoic quartzite, metavolcanic rocks, gneiss, granite, bull quartz, and cobbles and boulders of Pliocene basalt from the southern Los Pinos Mountains. Chert pebbles are present, but uncommon.

Younger fans and interfan drainages extend into the quadrangle from Sepultura, Bootleg, and smaller drainages from Los Pinos Mountains (Allen and Love, 2013). They deposit clasts dominated by Proterozoic granite with rare limestone clasts and common-to-uncommon quartzites, gneiss, bull quartz, and amphibolite. They join Turututu Draw and abut a north-south, down-to-the-east, Quaternary normal fault at the edge of Palo Duro fan deposits and soils. Preliminary soil profiles in the smaller, younger fans show diffuse relatively uniform calcic horizons mixing with red argillic horizons, indicative of an upbuilding calcic soil. This argues for significant and recent aggradation of these young fans.

Both the Palo Duro fan and the younger, smaller fans from Sepultura, Bootleg and smaller drainages have a significant mixture of alluvial and eolian sediment. On Palo Duro fan, these younger sediments partially fill the generally north to northwest trending swales, though evidence of alluvial overland flow is still present. The amount of eolian sediments decreases from south to north, presumably decreasing as a function of distance from the assumed source of Palo Duro Canyon to the south.

Younger deposits related to stream valleys and other slopes

Alluvial, colluvial, and eolian deposits mantle the lower valley margins and bottoms of all the stream valleys and swales on the quadrangle. Most of these deposits are latest Pleistocene and Holocene in age. The exceptions, however, are the colluvial-alluvial slopes downhill from fault scarps and some terrace risers which have developed over hundreds of thousands of years. Some of these old slopes have stage III+ to IV pedogenic calcium-carbonate horizons within a meter of the surface.

Previous work related to the Black Butte quadrangle

Previous geologic maps of the Black Butte area at scales larger than 1:500,000 have lumped the Quaternary units together into generalized piedmont deposits overlying Santa Fe Group basin fill (Darton, 1922; 1928), Wilpolt et al. (1946), Kelley (1977), Osburn (1984), and Connell (2004). The previous maps also present various interpretations of the Paleogene volcanic rocks in the area. Kelly (1977) also mapped a generalized terrace along the east side of the Rio Grande valley and at mouth of Abo

Arroyo. Myers et al. (1981) and Myers et al. (1986) began to delineate a few Quaternary units on their quadrangle maps to the east and south. Within the past 10 years, mappers for State Map projects have delineated more Quaternary units on surrounding 7.5-minute quadrangles (Love, 1999; deMoor et al., 2005; Luther et al., 2005; McCraw et al., 2006; Allen and Love, 1913).

Similarly, the presence of surface ruptures of faults has been noticed increasingly through time beginning with Darton (1928; none), Wilpolt et al. (1946, none), Kelley (1977; three), Machette and McGimsey (1982; two) Osburn (1984; one), and Olig et al. (2011; possibly 12). Our Black Butte 7.5-minute quadrangle geologic map shows eight distinct faults, but some have multiple strands, and others have no surface scarps.

Studies of the subsurface are primarily along U.S. 60 east-west, and north-south along the Five-Points and Beacon Forks roads into Sevilleta National Wildlife Refuge. Interpretations of COCORP seismic lines along the two roads (Brown et al., 1980; Cape et al., 1983; Larsen et al., 1986; deVoogd et al., 1988) were concerned with structure deep within the Rio Grande rift and not with shallow, near-surface fault blocks. Many interpret a subsurface shelf extending westward from Abo Pass before being truncated east of Bernardo (e.g. Brown et al. 1980). Sanford (1978) interpreted a rounded ridge-shaped gravity high extending north-northeast from the south under Black Butte. Gillespie et al. (2004) and Grauch et al. (2013) presented regional gravity anomaly maps of the Albuquerque basin which Rinehart and Love (2014) used to show that northwest-directed streams were following a gravity gradient downward to the northwest. Darton (1922) reported more than 150 m of gravel and red clay in water wells drilled along the railroad north of the Black Butte quadrangle, and residents report similar sedimentary units in their wells. Stellar Energy drilled an oil well on the south side of U.S. 60 northeast of Black Butte. It penetrated 155 m of basin fill before hitting basaltic andesite and ashflow tuffs, older Datil Formation volcaniclastics, Permian and Pennsylvanian sedimentary rocks at depths between 346 and 1065 m, and Proterozoic metamorphic rocks below that.

Important regional interpretations with broad geologic perspectives that are pertinent to Black Butte quadrangle include Kelley (1977), Hawley (1978), Chapin and Cather (1994), Connell (2004), Olig et al. (2011), Grauch et al. (2013), and other studies referenced therein.

Unit Descriptions

NEOGENE

QUATERNARY

Post-Santa-Fe-Group units common to whole map

Alluvium of stream valleys

Qay Channels and floodplains of major arroyo floors (Historic and Holocene)—Poorly to moderately sorted, unconsolidated pebble- to cobble- alluvium and fine- to coarse-grained sand with local accumulations of cobbles and small boulders in channels, and silt and clay in backwaters and floodplains. Sand colors generally range from 5YR light values to 10 YR light values. Underlies narrow- to-broad streams; channels are inset against low terrace and floodplain deposits. Includes active alluvium of Abo, Isabel, Pino, Turututu, and Maes drainages. Deposits are generally thin and range from less than 1 m to more than 4 m thick.

Qav Abandoned and active valley bottom alluvium recently incised by modern channels (Holocene and upper Pleistocene)—Poorly to moderately sorted, unconsolidated fine- to coarse-grained sand with local accumulations of cobbles and small boulders in channels, and silt and clay in backwaters and former floodplains. Sand colors generally range from 5YR light values to 10 YR light values. Soils, where developed, are thin and barely achieve even Stage I pedogenic carbonate horizons. Near Scholle, in Abo Canyon 19 km east of the quadrangle, Hall et al. (2012) obtained radiocarbon ages of 11,100 and 12,300 cal yr BP in a wet-meadow deposit at depths between 5.77 and 6.67 m in similar alluvium. Deposits are generally more than 2 m exposed and locally form bluffs several meters high.

Qam Alluvium, undivided deposits at intermediate valley-border levels along tributaries (upper to middle Pleistocene)—Weakly consolidated sand and gravel associated with modern drainages. Inset against older alluvium of large fans and is, where possible, divided locally into two subunits, **Qam_1** and **Qam_2**. Pedogenic carbonate horizons reach stage II. Colors are from 5YR to 10YR light values. Thicknesses are between 5 m to 10 m.

Qsy Swale bottom alluvium without inset channels or preserved eolian deposits, undivided (Holocene and upper Pleistocene)—Poorly to moderately sorted, unconsolidated fine- to coarse-grained sand and silt with rare local accumulations of pebbles. Colors are similar to **Qav**. Swales are inset below other alluvial terrace deposits, but have indistinct boundaries with flanking slope deposits. Deposits are generally thin and range from less than 1 m to more than 2 m thick.

Qso Alluvium with secondary eolian sediment in broad (50 m to 100 m) shallow (less than 10 m) swales (Holocene to middle Pleistocene)—Poorly to moderately sorted, unconsolidated fine- to coarse-grained sand and silt with rare local accumulations of pebbles, without inset channels or mappable eolian deposits of the Abo/Pino fan complex. Swales are inset below older alluvial deposits, but have indistinct boundaries with flanking slope deposits. Matrix is generally slightly reddish with a mixture of less than 5-cm diameter subangular clasts of Precambrian quartzite, granite, chert, and uncommon schist and gneisses (50-60%), sub-angular to sub-rounded limestone (30-40%), and blocky sub-angular red fine-grained laminated sandstone (10-20%). Channels are visible and nominally active. Eolian accumulations are thin without identifiable deposits of sand sheets, dunes or wind ripples. Soils are similar to surrounding units, but generally are Stage III to Stage IV. Thicknesses range from 1 m to 3 m.

Anthropogenic deposits

af Artificial fill (historic)—Dumped fill and areas affected by human disturbances. Mapped where disturbances are extensive; areas commonly include levees and small earth-fill dams, paved raised roads, and dairies.

Eolian deposits

Qe Eolian deposits, undivided (Holocene to upper Pleistocene)—unconsolidated, well sorted and locally stratified eolian sand in thin sheets and coppice dunes draped across pre-existing topographic features such as intermediate inset terraces, inactive stream channels and colluvial wedges. Colors are generally 10 YR light values. Thickness varies from less than 1 m to 5 m.

Playa deposits

Qpl Playa deposits with secondary eolian sediment in broad (50 m to 100 m) shallow (less than 5 m) closed basins (historic to middle Pleistocene)—Unconsolidated fine-grained sand, silt, and clay. Playas are inset below older alluvial deposits, but have indistinct boundaries with flanking slope deposits and swales. Many developed in grabens or low hanging-wall settings. **Qplo** deposits are in depressions developed on lower Pleistocene abandoned fan surfaces. Colors similar to surrounding slopes. Thickness ranges from 0 to 2 m.

Colluvial and slope deposits

Qc Colluvium undivided (Holocene to middle Pleistocene)—Poorly consolidated, poorly sorted, and poorly stratified, fine- to coarse-grained, clast- and matrix-supported deposits derived from a variety of mass-movement hillslope processes, including raveling of single clasts, debris flows, shallow slumps, and creep. overlying and interfingering with tributary alluvium at intermediate inset terrace levels. Clasts are typically rounded to subangular pebbles and cobbles reworked from units **Tlp**, **Ttr**, **Qsfp**, **Qpf**, **Qsx** and **Qsfd**. Colluvium is common on hillslopes and grades downslope to alluvium. Both are dissected. Thickens downslope from thickness of less than 1 m to thicknesses of 5 m.

Qsw Colluvium and slope-wash deposits on gentle slopes (historic to middle Pleistocene)—Poorly consolidated, poorly sorted, and poorly stratified, primarily sand- to clay-sized clasts, with matrix-supported larger pebbles derived from adjacent deposits via local hillslope processes and eolian contributions. Overlies and interfingers with tributary alluvium and swales. Locally dissected by rills and small gullies. Locally stable enough to develop stage 1-2 pedogenic carbonate horizons. Thickens downslope from less than 1 m to 5 m.

Qswf and Qcxd Colluvium and slope-wash deposits on slopes related to fault scarps (historic to middle Pleistocene)—Poorly consolidated, poorly sorted, and poorly stratified, primarily sand- to clay-sized clasts, with matrix-supported larger pebbles and cobbles derived from adjacent deposits uphill on fault scarps. Mass-movement hillslope processes, eolian contributions, and bioturbation cause poor sorting. **Qcxd** also includes poorly-exposed outcrops of coarse-grained cobbly alluvium from the Palo Duro fan interpreted to be interfingering with ancestral Rio Grande deposits (**Qsx**) along the fault scarp east of the pipeline along the northern boundary of Sevilleta National Wildlife Refuge. Overlies and interfingers with tributary valley alluvium at inset levels and in swales. Locally dissected by rills and small gullies. Thickens downslope from less than 1 m to 5 m.

Post-Santa-Fe-Group alluvium of young piedmont aprons and alluvial fans from west face of Los Pinos Mountains

Qpf Alluvium in fans and aprons along the west flank of the Los Pinos Mountains (Holocene and upper Pleistocene)—Poorly to moderately sorted, unconsolidated fine- to coarse-grained sand with local accumulations of cobbles and small boulders in channels and on intra-channel bars, and silt and minor clay in backwaters; grain sizes decrease down slope to distal run-out zones. These fans are graded to modern inset drainages, but commonly bury older fan deposits and soils which probably extend hundreds of m below the modern surfaces. Rounded "whalebacks" of Pleistocene alluvial deposits stick up 2-5 m above active channels, particularly along distal portions of the fans, but are too small in area to be mapped at 1:24,000. Fan-shaped alluvium from two major canyon drainages are mapped individually as **Qpfs** (Sepultura fan) and **Qpfb** (Bootleg fan) based on extent of active distributary channels.

Qfm Elevated, abandoned remants of alluvium between Sepultura Fan (**Qpfs**) and Bootleg Fan (**Qpfb**) (upper Pleistocene)—Poorly to moderately sorted, unconsolidated fine- to coarse-grained sand with local accumulations of pebbles and cobbles; grain sizes decrease down slope to distal inactive run-out channels. Stable portions of surface have stage I-II pedogenic carbonate horizons. Thickness is at least 3 m.

Post-Santa Fe Group alluvium on elevated valley margins

Rio Grande terrace deposits after abandonment of highest level of Rio Grande deposits

Qrgt2 Rio Grande alluvium, intermediate terrace deposits (middle Pleistocene)—White to pale-brown (10 YR 8/2-8/3; 7.5 YR 5/4), poorly consolidated, pebbly to cobbly sand and clast-supported gravel. On adjacent Abeytas quadrangle, lower (**Qrgt3**) and higher (**Qrgt1**) terraces are delineated (McCraw et al., 2007) , but not expressed on the Black Butte quadrangle. Unconformably overlies red sandstone, siltstone and conglomerate of unit **QTsp** on adjacent Abeytas quadrangle (McCraw et al., 2007). Cross-bedded gravels are generally pebbles smaller than 5 cm in diameter, but a few clasts are up to 20 cm in diameter. Pebbles consist of well-rounded extrabasinal clasts of igneous and metamorphic rocks, particularly orthoquartzite, and polished chert pebbles and cobbles. Sparse rounded pebbles of Rabbit Mountain (Jemez Mountains; 1.4 Ma) and East Grants Ridge (Grants; 3 Ma) obsidians are also present. Deposits sit between 43 and 50 m above the present Rio Grande floodplain.

Qsx2 Rio Grande alluvium, oldest terrace deposits (middle Pleistocene)—White to pale-brown (10 YR 8/2-8/3; 7.5 YR 5/4), poorly exposed, poorly consolidated, pebbly to cobbly sand and clast-supported gravel. Gravels are generally pebbles smaller than 5 cm in diameter, but a few clasts are up to 20 cm in diameter. Pebbles consist of well-rounded extrabasinal clasts of igneous and metamorphic rocks, particularly orthoquartzite, and polished chert pebbles and cobbles. Sparse rounded pebbles of Rabbit Mountain (Jemez Mountains; 1.4 Ma) and East Grants Ridge (Grants; 3 Ma) obsidians are also present. Deposits sit approximately 70 m above the present Rio Grande floodplain. Bluff line of terrace is along the northern edge of the Sunwell surface of Qsx deposits on the western part of U.S. Highway 60. Thickness is probably less than 5 m.

Alluvium of Abo and Isabel drainages inset after abandonment of highest level of Rio Grande deposits

Qaom Alluvium, undivided inset terrace and fan deposits (upper middle Pleistocene)—unconsolidated sand and gravel associated with valley Abo valley borders (north and south) and inset fans upstream from mouth of Abo Valley that also extend along the western edge of the quadrangle to the southwest. Gravels are subangular to subrounded pebbles and cobbles of limestone, sandstone, granitic, and metamorphic rock types indicating derivation from uplands to the east. The gravel matrix and finer-grained beds of alluvium are typical Abo colors (5YR 7/3). Inset against the Sierra Ladrones formation. Overlies all of the Rio Grande terraces of McCraw et al. (2007)

Qrgt1, **Qrgt2**, and **Qrgt3** Pedogenic carbonate horizons reach stages II to III—Locally divided into subunits of **Qaom1** and **Qaom2** based on inset terrace levels. Thickness is between 5 m and 10 m.

Qaa Alluvial deposits along discrete paths of the Abo drainage after valley entrenchment began (middle Pleistocene)—Unconsolidated gravel and sand (colors) associated with valley borders, particularly south of Abo Valley and along Isabel Draw. Gravels are subangular to subrounded pebbles and cobbles of limestone, sandstone, granitic, and metamorphic rock types indicating derivation from uplands to the east. Rare clasts of rounded Rio-Grande-derived pebbles are reworked from older **Qsx** deposits to the east. Inset against the Sierra Ladrones Formation. Pedogenic carbonate horizons reach stages II to III. **Qaa1** is highest and easternmost inset level of inset fan deposits on both sides of Abo valley, roughly 30-35 m above the valley floor, and **Qaa2** is locally inset below that. **Qaa3** is slightly inset below that and extends farther west on both sides of the valley. Units **Qaa4** through **Qaa9** occur along the Abo-Isabel drainage divide farther west and extend down Isabel Draw to the southwest. **Qaa6** consists of coarse cobbles of Abo alluvium at an intermediate terrace level near the head of Isabel Draw. **Qaa9** is a lower inset terrace along Isabel Draw and one of its tributaries that contains a mixture of Abo clasts and locally reworked Rio Grande sediments derived from **Qsxo and Qsx**. Thicknesses range between 3 and 7 m.

Alluvium of Amizette Draw and east Vargas fans after abandonment of highest level of Rio Grande deposits

Qvf Alluvium at low and intermediate levels of valley of Amizette Draw and east Vargas fans (upper to middle Pleistocene)—unconsolidated sand and gravel associated with paths of Amizette drainage and its fans on easternmost **Qsx**. Inset against older alluvium of large Santa-Fe-age Abo fans such as **Qafft1** as the drainage incised across the Military Highway fault zone. Divided into packages of inset fans from oldest to youngest: **Qvf1**, **Qvf2**, **Qvf3**, and **Qvf4**. **Qvf4** connects upstream with **Qsy** in the valley of Amizette Draw. Pedogenic carbonate horizons reach stage II on **Qvf1**. Pebbles consist of a mixture of reworked Abo and Rio Grande gravels. Colors are from 5YR to 10YR light values. Thicknesses are estimated to be between 3 m to 7 m.

Alluvium of Pino Draw after abandonment of highest level of Rio Grande deposits-- Alluvium of Pino Draw upstream from Black Butte

Qap Alluvium at an intermediate level between **Qafi** and **Qam** along the valley of Pino draw (Holocene to upper Pleistocene)—unconsolidated sand and gravel associated with the path of Pino Draw and interaction with toes north-trending piedmont from the south (**Qpbs**, **Qfm**, and **Qpfs**). Sediments are generally slightly reddish poorly sorted sands with small gravels and a Stage II soil. Gravels are subangular and are dominated by granite, granitic gneiss, schist, chert, and quartzite with uncommon limestone and rare red sandstone clasts. It is between less than 1-m to 2-m above the active channel of Pino Draw with a diffuse upper edge. Sediment thicknesses range from less than 1 m to 2 m.

Qafi Alluvium at intermediate levels of upper valley of Pino Draw (upper to middle Pleistocene)—unconsolidated sand and gravel associated with inset fans and paths of Pino Draw. Inset below higher Abo fan deposits **Qafo1** and **Qafo2** as the drainage incised across the Military Highway fault zone. The sediment has a matrix of pale reddish poorly sorted fine- to coarse-grained sand with subangular granitic, metamorphic, limestone, fine-grained red sandstone common gravels and uncommon cobbles reflective of upstream terrains and reworking of clasts from the older Abo fan deposits (**Qafo1** and **Qafo2**). Clasts are approximately 60% granitic and metamorphic rocks, 30% limestone and 10% red sandstone. Divided into packages of inset fans from oldest to youngest: **Qafi0**, **Qafi1**, **Qafi2**, and **Qafi13**. Inset levels north of Pino Draw may reflect paths of the

Abo drainage before Pino Draw was established. Soils range from Stage III in **Qafi2** and **Qafi3**, to Stage III/IV on **Qafi1** to Stage IV/IV+ on **Qafi0**, but the proportions of clast lithologies remain approximately constant.

Alluvium of Pino Draw downstream from Black Butte

Qapf Alluvium along low-level terrace in Pino valley and fan on Rio Grande terrace (upper to middle Pleistocene)—unconsolidated, poorly sorted, reddish sand and gravel along terrace of Pino Draw and its fan on westernmost eroded **Qsxo** and **Qrgt2**. Clasts are a mixture of subangular Proterozoic quartzites and other metamorphic rocks, limestone, red sandstone, and well-rounded pebbles of ancestral Rio Grande gravel. Inset against older alluvium and general Santa-Fe Group basin-fill **QTsps**. Elevation of tread above Pino Draw is approximately 5 m. Pedogenic carbonate is Stage II. Thickness ranges from 0 to 7 m.

Qpfo Alluvium on intermediate terrace of Pino Draw deposited as fan on Rio Grande deposits (upper to middle Pleistocene) — unconsolidated sand and gravel of Pino Draw deposited as a valley-mouth fan on **Qsxo**. Clasts are a mixture of subangular Proterozoic quartzites and other metamorphic rocks, limestone, red sandstone, and well-rounded pebbles of ancestral Rio Grande gravel. Inset against **Qsxo** and general Santa-Fe Group basin-fill **QTsps**. Elevation of tread above Pino Draw is approximately 7-10 m. Pedogenic carbonate is Stage III. Thickness ranges from 0 to 5 m.

Alluvium of Turututu Draw

Qatf Alluvium along low-level terrace in Turututu valley and fan on Rio Grande terrace (upper to middle Pleistocene)—unconsolidated sand and gravel along terrace of Turututu Draw and its fan on westernmost eroded **Qsxo** and **Qrgt2** and on fan of Pino Draw (**Qapf**). Grades upstream and upslope to **Qats**. Inset against **Qsxo** and general Santa-Fe Group basin-fill **QTsps**. Clasts are a mixture of subangular Proterozoic quartzites and other metamorphic rocks, limestone, red sandstone, basalt, basaltic andesite, and well-rounded pebbles of ancestral Rio Grande gravel. Elevation of tread above Turututu Draw is approximately 5 m. Pedogenic carbonate is Stage II. Thickness ranges from 0 to 7 m.

Qats Alluvium and colluvium along slopes in Turututu valley derived from adjacent basin-fill deposits (middle to upper Pleistocene)—unconsolidated sand and gravel along valley-margin slopes of Turututu Draw below the level of **Qsx** in contact with **QTsps**. Clasts are a combination of well-rounded Rio Grande gravel and subangular Proterozoic quartzites and other metamorphic rocks, limestone, red sandstone, and basaltic andesite. Matrix derived from **QTsps** commonly is pink (7.5 YR 7/3), reddish-yellow (5YR 6/6), red (2.5 YR 5/6) and reddish brown (2.5 YR 4/4). Locally forms slight intermediate terrace. Thickness less than 4 m.

Qatfo Alluvium on high terrace of Turututu Draw deposited on local inset Rio Grande deposits (middle Pleistocene)—White to pale brown (10 YR 8/2-8/3), unconsolidated sand and gravel of Tutututu Draw perhaps deposited as a valley-mouth fan on **Qsx2**. Clasts are a combination of well-rounded Rio Grande gravel and subangular Proterozoic quartzites and other metamorphic rocks, limestone, red sandstone, basalt, and basaltic andesite. Pedogenic carbonate is Stage III. Thickness ranges from 0 to 5 m.

Qae Alluvium and eolian deposits, undivided (Holocene to upper Pleistocene)—Poorly consolidated, poorly sorted and poorly stratified tributary alluvium and eolian sand and silt sheets in tributary drainages and on intermediate inset terrace levels; thickness varies from less than 1 m to 5 m. Locally, **Qae$_1$** fills older swales closer to sediment source terranes than **Qsy** and **Qso**, and has accumulated more calcium carbonate and iron-oxides in the B horizon and has more reworked pebbles at the surface than **Qae$_2$**. **Qae$_1$** is traceable down drainages to the same level as **Qay**, although in some reaches **Qae$_1$** grades down to **Qav, Qas,** or **Qsy**. **Qae$_1$** deposits are between 1 m and 5 m thick. **Qae$_2$** is younger and has less pedogenic calcium carbonate and iron oxides, and few pebbles at the surface. **Qae$_2$** is traceable down drainages to the **Qay** or **Qav** level. **Qae$_2$** deposits are generally thin and range from less than 1 m to more than 3 m thick.

Santa Fe Group

Qsx Sierra Ladrones Formation, axial-fluvial deposits (upper Santa Fe Group, lower Pleistocene)—White-to-pale brown (10 YR 8/2-8/3) pebbly medium-coarse sand. Pebble and cobble gravels consist of well-rounded volcanic rocks (~40%), granite (25%), orthoquartzite (20%), polished multicolored chert (15%), and uncommon subangular, clasts of the fan facies reworked into the fluvial deposits. The most distinctive clasts are obsidians from Rabbit Mountain (Jemez Mountains; 1.4 Ma) and East Grants Ridge (Grants, 3 Ma). Associated with the upper part of this unit are rare clasts of ashflow tuff probably derived from floods along the Rio Grande after the upper Bandelier Tuff eruption, documented farther north east of the Rio Grande. **Qsx1** is a coarse cobble unit that locally holds up an elevated remnant of **Qsx** beneath the communications tower along U.S. Highway 60 west of Pino Draw crossing. The unit is poorly exposed. Unit is 0-7 m thick.

Qsxo Sierra Ladrones Formation, mixed axial-fluvial deposits and distal fans (upper Santa Fe Group, lower Pleistocene)—Interbedded sands and gravels from the Rio Grande and alluvial fans from eastern and southeastern sources. Fluvial gravels contain abundant well rounded clasts of volcanic rocks (~40%), granite (25%), rounded orthoquartzite (20%) and polished rounded chert (15%) whereas local fan alluvium clasts are subangular to subrounded limestone, sandstone, Proterozoic granitic and metamorphic rocks, and basalt. The geochemical fingerprint of pumice clasts as pebbles, granules, and a pumice-raft deposit near the base of exposures is consistent with the Guaje pumice eruption at the base of the Otowi Member of the Lower Bandelier Tuff (1.61 Ma; Kelley et al. 2013). The unit is poorly exposed on hillslopes and in arroyo banks on the western side of the quadrangle. Unit combined with **Qsx** is estimated to be 60 meters thick on the west side of the quadrangle, but thins to 0 at the river's old bluff line to east.

QTsps Sierra Ladrones Formation, sandstone- and mudstone- dominated generalized piedmont deposits (upper Santa Fe Group, lower Pleistocene to Pliocene)—Pink (7.5 YR 7/3), reddish-yellow (5YR 6/6), red (2.5 YR 5/6) and reddish brown (2.5 YR 4/4), poorly exposed, unconsolidated to poorly consolidated, uncemented to cemented, mudstones and sandstones with moderately sorted tabular, crossbedded sandstone and scattered, irregular pebbly sandstone and conglomeratic sandstone lenses. Beds commonly form sequences with a basal conglomerate that fines upward into sand and mud that is locally capped by calcic paleosols, thin rhizoconcretionary beds, and cemented tufa-like spring-groundwater-precipitated deposits. Pebbles comprised of subangular Proterozoic granite and metamorphic rocks. Sandstone beds tend to comprise less than 30% of the unit. Mudstone units locally contain concretionary masses of gypsum crystals. Commonly overtopped by fan deposits (e.g. **Qsfd**) and ancestral Rio Grande deposits (**Qsx**). May include tongues of **Qsxo** in west-central part of quadrangle. Exposed thickness in valley walls ranges from 0 to more than 20 m and local water wells penetrate at least 165 m.

Qabd, Qafo1, Qafo2 Sierra Ladrones Formation, upper-level coarse-grained fan deposits from Abo drainage (upper Santa Fe Group, lower Pleistocene)—Pink to reddish-yellow (7.5YR 6/6-7/3), poorly consolidated, uncemented to locally well cemented, poorly to moderately sorted conglomerate, pebbly sand, and red mudstone. Because of pedogensis, some stripped surfaces are gray to pale cream-colored (10YR7/2-7/3), poorly consolidated, uncemented to locally well cemented, poorly to moderately sorted conglomerate and pebbly sand. Locally the surfaces developed extensive desert pavement and some clasts are covered with rock varnish. Bedding follows planar westward slope. Clasts include subangular to subrounded pebbles to boulders of rocks from the Abo Pass area, including red sandstones, brown-to-tan sandstones, limestones, granite, granite gneiss, amphibolite, metarhyolite, and quartzite. Has a scoured basal contact with underlying finer-grained deposits. Locally forms bluff line cut by axial fluvial deposits of ancestral Rio Grande (**Qsx**). Pedogenic carbonate horizon at top of unit reaches at least stage 4. **Qabd** underlies high planar surface on north side of Abo valley. **Qafo1** and **Qafo2** underlie high planar surfaces on the south side of Abo valley, with **Qafo2** slightly inset below **Qafo1**. Exposed thickness of whole unit ranges up to 20 m.

Qafbs, Qaftt1, Qaftt2 Sierra Ladrones Formation, slightly inset upper-level coarse-grained fan deposits from Abo drainage (upper Santa Fe Group, lower Pleistocene)—Pink to reddish-yellow (7.5YR 6/6-7/3), poorly exposed, poorly consolidated, uncemented to locally cemented, poorly to moderately sorted cobble and pebble gravel, and pebbly sand. These broad inset fan remnants are below the maximum aggradational sufaces of **Qafo1** and **Qafo2**, but their connection to inset Abo-valley pathways farther east remains problematic. Locally some clasts are covered with rock varnish. Bedding follows planar westward slope. Clasts include subangular to subrounded pebbles to cobbles of rocks from the Abo Pass area, including red sandstones, brown-to-tan sandstones, limestones, granite, granite gneiss, amphibolite, metarhyolite, and quartzite. Has a scoured basal contact with underlying finer-grained deposits of **QTsps**. Pedogenic carbonate horizon 1-2 m thick at top of unit reaches stage 3. **Qafbs** underlies high inset planar surface on south edge of Abo valley and more extensive surface along north side of Amizette Draw. The surface of this deposit shows maximum amount of offset across Military Road fault zone. **Qaftt1** underlies a slightly lower planar surface on the south side of Amizette Draw, and **Qaftt2** is local and slightly inset below **Qaftt1**. Exposed thickness of whole unit ranges up to 5 m.

Qsfd Sierra Ladrones Formation, coarse-grained fan deposits from Palo Duro drainage (upper Santa Fe Group, lower Pleistocene)—Pink to reddish-yellow (7.5YR 6/6-7/3), poorly consolidated, uncemented to locally well cemented, poorly to moderately sorted conglomerate and pebbly sand. Bedding follows planar northwestward sloping surfaces with local desert pavement. Clasts include subangular to subrounded pebbles to boulders of rocks from the southern Los Pinos Mountains, including granite, granite gneiss, amphibolite, metarhyolite, quartzite, sandstone, limestone, basalt, basaltic andesite, and rhyolite. Has a scoured basal contact with underlying finer-grained deposits. It overlies top of axial fluvial deposits of ancestral Rio Grande (**Qsx**) and general piedmont deposits (**QTsps**). Medial and proximal parts of the fan(s) on the Becker SW quadrangle show inset elevations and two or more episodes of fan activity not mapped on the Black Butte quadrangle. Thickness ranges up to 15 m.

PALEOGENE

Tlp La Jara Peak Basaltic Andesite, (probably tongue 5, upper Oligocene)—Mostly medium gray to purplish gray, massive and platy to vesicular basaltic andesite lavas characterized by moderately abundant (5–10%) fine- to medium-grained phenocrysts of olivine, usually altered to reddish brown iddingsite. Phenocrystic plagioclase is typically absent. Thin flows (3-6 m) commonly exhibit vesicular tops and reddish basal breccia zones. Two flows of Tlp at the top of Turututu (Black Butte) rest on Vicks Peak Tuff and have a K-Ar age of 24.3 ±1.5 Ma (Bachman and Mehnert, 1978). This age is probably too young because two-thirds of basaltic andesite eruptions are between 27.2 and 28.7 Ma $^{40}Ar/^{39}Ar$ ages (Chapin et al., 2004). Maximum thickness is 13 m. (Description modified from William McIntosh, written communication, 1 April 2013)

Ttr Rhyolitic tuffs beneath Tlp on Turututu (Oligocene)—Vicks Peak Tuff (17-20 m), La Jencia Tuff (13 m), and Hells Mesa Tuff (> 12 m) at 28.4, 28.7, and 32 Ma $^{40}Ar/^{39}Ar$ ages respectively (Chapin et al., 2004). Vicks Peak Tuff: densely welded, brown to light brownish gray and light gray, phenocryst poor, pumiceous, rhyolite ignimbrite. Pervasive well developed compaction foliation, and large “sandy” (vapor phase) pumice lapilli up to 30 cm long. La Jencia Tuff: densely welded light gray, pale red and grayish red, phenocryst poor, rhyolite ignimbrite. Contains sparse (3–5%) phenocrysts of sanidine and quartz with rare plagioclase and biotite. Hells Mesa Tuff: Pale reddish gray to light gray, mostly densely welded, phenocryst-rich (40–50%), quartz-rich, rhyolite ignimbrite. Typically contains abundant medium grained (1–3 mm) phenocrysts of sanidine, plagioclase, quartz and minor biotite. Quartz is minor component (1-2%) in thin basal zone (not exposed here). (Description modified from William McIntosh, written communication, 1 April 2013).

Td Datil Group, intermediate-composition volcanic and volcaniclastic rocks (Lower Oligocene and Upper Eocene)—In subsurface in cross section only, beneath rhyolitic tuffs under Black Butte and elsewhere. Spears Formation of Datil Group exposed along Palo Duro Canyon on the Becker SW and the La Joya quadrangles to the south-southwest where it rests on Permian rocks. May be unidentified unit between tuffs and Permian Yeso Formation in local oil well stratigraphic test (B. Black, written communication, 2014).

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