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

By
Colin T. Cikoski[1], W. John Nelson[2], Daniel J. Koning[1], Scott Elrick[2], and Spencer G. Lucas[3]

[1] New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801
[2] Illinois State Geological Survey, 615 East Peabody Drive, Champaign, IL 61820
[3] New Mexico Museum of Natural History, 1801 Mountain Road NW, Albuquerque, NM 87104-1375

June, 2017

New Mexico Bureau of Geology and Mineral Resources
Open-File Geologic Map OF-GM 262

Scale 1:24,000

This work was supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program (STATEMAP) under USGS Cooperative Agreement G16AC00287 and the New Mexico Bureau of Geology and Mineral Resources.

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

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1. Introduction

1.1. Geologic and geographic setting

The Black Bluffs 7.5-minute quadrangle straddles the Rio Grande roughly 12 km north of the city of Truth or Consequences. The quadrangle covers much of the northern half of Elephant Butte reservoir, and extends from the base of the Fra Cristobal Mountains on the east to about 5 km up the piedmont of the San Mateo Mountains and Sierra Cuchillo to the west. It covers the outlet of Alamosa Creek as it enters the inner Rio Grande valley, and includes such geographic features as The Narrows, Black Bluffs, White Cliffs, and North and South Monticello Point. The quadrangle was largely mapped in 2015-2017, during which time the Elephant Butte Lake level was particularly low, with the lake restricted to the south half of the quadrangle and numerous previously-concealed features then exposed. The area along the reservoir and Rio Grande floodplain lies on Elephant Butte Lake State Park land; private land is found along the eastern margin of the quadrangle, along Alamosa Creek, and in the area of Highland Estates in the southwest of the quadrangle; and the remainder is mostly administered by the BLM. Vegetation is Chihuahuan Desert scrubland and riparian. Non-inundated land surface elevation ranges from about 1334 m above mean sea level (amsl) at the level of the lake to 1547 m amsl at the highest point of Crater Hill in the northwest corner of the quadrangle.

Geologically, the quadrangle lies mostly in the southern portion of the Engle basin of the Rio Grande rift, with the far southeastern corner lying in the Cutter Sag. The Engle basin is an east-tilted rift basin down-dropped along the Hot Springs and Walnut Canyon faults, which lie at the base of the Cutter Sag and Fra Cristobal Mountains, respectively. The basin is of at least Plio-Pleistocene age, during which time it accumulated sediments delivered to the basin by an ancestral Rio Grande as well as piedmont deposits derived from both the Fra Cristobal Mountains to the east (eastern piedmont alluvium) and the San Mateo Mountains, Sierra Cuchillo, and Mud Springs Mountains to the west (western piedmont alluvium). From ~5 to ~0.8 Ma (Mack et al., 2006), the Rio Grande and its tributaries overall aggraded and alluvial sediment accumulated. Since ~0.8 Ma, however, these streams have overall incised, with periods of stability and/or aggradation resulting in flights of terrace deposits along both the Rio Grande and its tributaries. The highest constructional surface associated with the aggradational phase is here referred to as the Cuchillo surface (Lozinsky and Hawley, 1986; McCraw and Love, 2012), and the sediment below this surface that accumulated coeval with an ancestral Rio Grande is referred to the Palomas Formation of the Santa Fe Group (Lozinsky and Hawley, 1986). The aggradational phase was punctuated by a series of basaltic volcanic eruptions associated with the Caballo (as called Engle and Cutter Sag) volcanic field, several vents of which are exposed on the quadrangle.

The Cutter Sag forms part of the uplifted southeastern boundary of the Engle basin. However, Rio Grande rift-related uplift of the Sag was relatively weak compared to the Fra Cristobal and Caballo uplifts to the north and south, respectively; rocks as old as Precambrian are exposed in the latter two uplifts, while the oldest rocks exposed in the Sag are Cretaceous strata. The Cutter Sag occupies a low-relief accommodation zone (Cutter Sag transfer zone of Mack and Seager (1995), Cutter Sag accommodation zone of Seager and Mack (2003)) that transfers extensional strain between the Hot Springs-Caballo fault system at the west base of the Caballo Mountains to the Walnut Canyon fault at the west base of the Fra Cristobal Mountains. As this area was a weak uplift through the Plio-Pleistocene, Palomas Formation alluvial sediment is only locally found here.

This report will focus on the Plio-Pleistocene Engle basin fill. For more information on the underlying bedrock and pre-Pliocene structure, see Nelson et al. (2012) and Nelson et al., (in prep.).

1.2. Previous work

Warren (1978) mapped much of the eastern piedmont and intercalated volcanic rocks, as well as the Cretaceous rocks in the southeastern corner of the quadrangle, as a part of his thesis studies. His work concentrated on the volcanic strata, and gave particular attention to the upper mantle-lower crustal xenoliths that occur in many of the basalt flows. Many of his names for volcanic features are adopted herein. He did not attempt to subdivide the Palomas Formation alluvium, however.

Lozinsky (1985) studied the late Cenozoic geology of the Elephant Butte Lake area, including the southernmost portion of this quadrangle, providing the first detailed study of the Palomas Formation in this area. He additionally mapped the Cretaceous strata of the Cutter Sag in the far southeast of the corner and further south. The focus of his work was further south, however, on the Elephant Butte quadrangle.

Several authors have studied the Fra Cristobal Mountains. Nelson et al. (2012) provided a recent published summary, while Nelson et al. (in prep.) will provide a more detailed review of the stratigraphy and structural geology of the area. These authors gave substantial attention to the older structures and Cutter Sag portion of the quadrangle, but left the Palomas Formation and intercalated volcanic rocks largely undifferentiated.

Detailed study of the Palomas Formation of the Engle basin presented here is largely original. However, several studies have been performed further south in the Palomas basin (cf., Seager and Mack, 2003; Mack et al., 2006; Mack et al., 2012; Koning et al., 2015; Jochems, 2015; Jochems and Koning, 2015; Jochems and Koning, 2016).

1.3. Methods

Geologic mapping was performed mainly during the years 2015-17 using standard methods (e.g., Compton, 1985). Field mapping was supplemented with remote mapping using 2009-vintage digital stereo aerial imagery using the ERDAS StereoAnalyst extension to the ESRI ArcMap software package. Data was compiled into a GIS geodatabase using ESRI's ArcGIS software platform. Geologic terms used herein are after Compton (1985), soil terms after Birkeland (1999), carbonate horizon stages after Gile et al. (1966) and Machette (1985), diatreme and maar terminology after White and Ross (2011), and color notation after Munsell Color (2009). Coordinates are given in Universal Transverse Mercator (UTM) coordinates after the NAD83 Zone 13S datum.

1.4. Acknowledgements

We thank J. Michael Timmons, Geologic Mapping Program Manager at the NMBGMR, and the USGS STATEMAP program for funding to conduct this study. We thank Tom Waddell and E. D. Edwards, former and current managers of the Armendaris Ranch, for access to ranch lands and the east side of the quadrangle. Cartography was provided by the NMBGMR map production group, coordinated by Phil Miller.

2. Late Cenozoic Geology

In anticipation of a more detailed, peer-reviewed article, the Late Cenozoic stratigraphy is only briefly reviewed here. The western and eastern sides of the inner Rio Grande valley will be discussed separately.

2.1. Eastern stratigraphy

The oldest Palomas Formation unit exposed on the eastern side of the quadrangle is an interval of interbedded piedmont conglomerate and sands/sandstones that are distinctly rich in gravels of Cretaceous sedimentary lithologies (Tpel). These are exposed along drainages south of the Black Mesa maar in depositional contact with underlying Cretaceous rocks, and along the east side of the Black Bluffs maar in fault contact with Cretaceous rocks. Between the Hackberry and Hot Springs faults, the top is marked by a weak paleosol bearing a profile with a cambic (Bw) horizon overlying a carbonate (Bk) horizon with Stage I morphology. The preservation of this soil here indicates a lack of erosion prior to deposition of the overlying Tpal axial sandstone unit. In contrast, in the footwall of the Hackberry fault, the upper contact is notably scoured, with the Tpel unit locally entirely removed by erosion.

Overlying Tpel is an interval of white, trough cross-stratified, quartz-rich sandstones with trace clays and siliceous gravels, interpreted to be deposits of the axial ancestral Rio Grande (unit Tpal). These deposits are exposed along the eastern margin of the quadrangle from Black Bluffs to the latitude of White Cliffs, extending off-quadrangle to the east. Northeast of the Black Bluffs maar, Tpal sandstones dip gently (maximum measured dip of 15°) to the northwest, and are overlain with angular unconformity by upper piedmont deposits (Qpeu). In the footwall of the Hackberry fault, this unconformity removes much of the unit.

From south of Black Mesa and northward, Tpal is conformable overlain by a middle piedmont unit that can be subdivided into conglomerate-dominated (Tpem) and sandstone-dominated (Tpes) subunits. The middle piedmont subunits interfinger in hillslopes between Black Mesa and White Cliffs, with Tpem occurring up-gradient (eastward) of Tpes, and the two units likely reflect coarser-grained proximal and finer-grained distal piedmont facies. In slopes along the eastern margin of the inner Rio Grande valley, a few intervals of axial Rio Grande pebbly sands/sandstones can be found interfingering with Tpes (unit Tpae, mapped as lines), indicating that the distal piedmont facies interfingered with the axial-fluvial facies further down-gradient (westward), although the bulk of the axial-fluvial facies has apparently been removed by erosion.

Toward the top of the middle piedmont unit, a thin discontinuous pyroclastic unit occurs (Tmpl) that can be followed into the Black Mesa maar, most clearly in the northeastern corner of the maar, where it grades into the pyroclastic diatreme unit Tbmd. The diatreme underlying the Black Mesa maar is only locally exposed beneath a sequence of basalt flows which flooded the maar crater. Two flow breaks define up to three separate flows in the Black Mesa maar; however, the upper flow break is discontinuous, and hence the upper two flows are mapped together as QTbbmu, while the lowest of the three is mapped as Tbbml. One or more of these flows likely correlates to the basalt of Walnut Canyon (Qbwc), although the basalts are not distinct enough to make a certain correlation. Bouldery conglomerate interfingers with the basalts in the Black Mesa maar (Tbmf), apparently reflecting local collapses of the maar crater wall into the crater. The center of Black Mesa is marked by a set of low hills underlain by cinder (QTbbmc).

Middle piedmont sediments continue above the Tmpl pyroclastic unit up to the base of a laterally continuous basalt (basalt of Walnut Canyon, Qbwc) and an overlying, extensive pyroclastic interval (Qmpu). A ^{40}Ar/^{39}Ar age of 2.50 ± 0.06 Ma (Peters, 2016; this report) for the basalt of Walnut Canyon places the basalt toward the base of the Pleistocene in the Galesian age. This basalt erupted from vents northeast of Black Mesa along the base of the Fra Cristobal Mountains, and flowed down the piedmont to at least the longitude of the modern inner Rio Grande valley. It is cut by both the Ocotillo diatreme (Tomd) and the White Cliffs maar crater, indicating the basalt predates the emplacement of the diatreme and eruption of the maar. The overlying pyroclastic unit Qmpu is interpreted to be mainly the outflow from the White Cliffs maar, as 1) the unit is thickest in the vicinity of White Cliffs, 2) coarse basalt bombs up to 0.5 m across are found around the maar, and 3) high energy depositional structures such as erosive undulatory bedding and swooping trough cross-stratification are found around the maar, but not further away. However, in the vicinity of the Ocotillo diatreme, Qmpu locally consists of two distinct pyroclastic intervals separated by a thin alluvial deposit, suggesting that at least locally part of Qmpu may be the product of a pyroclastic eruption from the Ocotillo diatreme. The relative order of volcanic events (intrusion of the Ocotillio diatreme versus eruption of the White Cliffs maar) is not certain.

No sedimentary maar in-fill was found associated with the Ocotillo diatreme. The White Cliffs maar crater filled with a variety of lake sediments, principally white, planar-laminated, siliceous muds that grade upsection into gypsiferous light gray to olive brown muds and fine quartz sands. Local limestones are also found, at least along the southern margin of the maar crater. Sediments dip gently toward the center of the maar, with dip magnitude decreasing upsection, suggesting some measure of syndepositional subsidence of the maar crater floor.

The outflow pyroclastic unit Qmpu is overlain by the basalt of Crater Hill (Qbch) in outcrop to the southwest of Crater Hill. This basalt has a ^{40}Ar^{39}Ar age of 2.15 ± 0.04 Ma (Peters, 2016), constraining the timing of the Ocotillo intrusion and White Cliffs eruption to between 2.5 and 2.15 Ma. The basalt of Crater Hill erupted from the Crater Hill cone, a relatively well-preserved cinder cone (units Qbchc, Qbchp) in the northwest of the quadrangle that appears to have a breached western flank from which the basalt presumably exited the cone.

The sequence of volcanic rocks Qbwc-Qmpu-Qbch is used to divide the middle piedmont units (Tpes, Tpem) from the upper piedmont unit Qpeu. Qpeu is notably less well-cemented and less well-exposed as compared to Tpes and Tpem, but appears to be gravel/conglomerate-dominated across its extent. Down-gradient (westward), it interfingers with axial pebbly sands of the ancestral Rio Grande, but due to poor exposure the two units cannot be mapped separately where interfingered; instead, the interfingering zone is mapped as a single unit, QTpai (or Qpai, where the presence of underlying volcanic units constrains the age of the deposit to Quaternary). Uncemented, poorly-exposed gravels and sands between Black Bluffs and Black Mesa, which overlie the lower units Tpal and Tpel with angular unconformity, are also interpreted based on the lack of cementation to belong to the upper piedmont unit. In addition, a poorly-cemented sand/sandstone-dominated unit (Qpes) that is restricted to an area southeast of Black Mesa is also interpreted to be a subunit of the upper piedmont unit. Qpes unconformably overlies Tpal with a scoured base that locally removes Tpal from the surface. In general, the top of the upper piedmont unit is not marked by a well-developed soil, suggesting that the Cuchillo surface, which is typically capped by a cemented carbonate horizon with Stage III or IV morphology (McCraw and Love, 2012), is not preserved within the quadrangle on the east side of the Rio Grande. The possible exception is at the top of the Qpes unit, where locally an eroded Stage III carbonate horizon can be found.

The sequence described above is fairly well-constrained by stratigraphy and forms the core of the stratigraphic sequence for the east side of the quadrangle. Additional elements include (from south to north) the basalt of Little Kettle Top Butte, the Black Bluffs maar, the pyroclastics of Massacre Gap Canyon, the basalt of the Rio Grande and associated pyroclastics, and the basalt of the monocline. The basalt of Little Kettle Top Butte (Qblk) caps an isolated butte southeast of Black Bluffs, overlying axial Rio Grande sediments and a thin pyroclastic interval (Qmpk). Due to their isolation, these units could not be definitively correlated to other on-quad units. However, unit Qblk occurs at comparable elevation to an extensive basalt flow occurring off-quad to the east and southeast (e.g., Lozinsky, 1985). These off-quad flows surround a cinder cone that Bachman and Mehnert (1978) K-Ar dated to 2.2 ± 0.4 Ma (see also Wilks and Chapin, 1997), suggesting a Lower Pleistocene (Galesian) age for the basalt of Little Kettle Top Butte.

The Black Bluffs maar crater clearly cuts unit Tpal and is overlain by Qpeu. Through much of the maar, the underlying diatreme pyroclastics (Tbbd) are exposed. Sedimentary crater fill (Tbbf) is only found along the eastern side of the maar. Both units are locally capped by basalt from a vent immediately southeast of the maar (Tbbb). The eruption of the Black Bluffs maar is broadly constrained to between deposition of Tpal and Qpeu.

The pyroclastics of Massacre Gap Canyon unit (Tmpm) includes three outcrops of pyroclastics occurring in the immediate footwall of the Hot Springs fault between the Black Bluffs and Black Mesa maars. The middle of these outcrops is the largest, and bears moderately (20-26°) west-southwest-dipping pyroclastics that are unconformably overlain by post-Santa Fe Group alluvium, sharply truncated on the west by the Hot Springs fault, and possibly inset against Tpal to the east. The contact with Tpal is not well exposed; however, the pyroclastics occur at a lower elevation that adjacent Tpal, and Tpal in the vicinity of Tmpm is highly deformed, suggesting that Tmpm may have erupted through Tpal and in the processes deformed the surround strata. Tmpm may be a poorly exposed diatreme. Its emplacement age is suggested to be comparable to that of the Black Bluffs diatreme.

The basalt of the Rio Grande (Qbrg) crops out along the north end of the quadrangle in the northeast corner, overlying a pyroclastic interval (Qmpg) that bears large basaltic bombs up to 0.7 m across, indicating a nearby source vent. Warren (1978) proposed that an unexposed Rio Grande maar occurs somewhere in this area, and we concur that a vent likely lies nearby. Qbrg intercalates with interfingering axial-fluvial sediments and eastern piedmont sediments (unit QTpai) and overlies the basalt of Mitchell Point (Tbm) in outcrop along its western extent. The timings of eruption for units Qbrg and Qmpg relative to the Qbwc-Qmpu-Qbch marker horizon is not entirely clear, but Qbrg and Qmpg are here suggested to be of comparable age to Qbch and Qmpu.

The basalt of the monocline (Tbmn) crops out only in the far northeastern corner of the map area. It erupted from a vent off-quadrangle to the east just inside the Fra Cristobal Mountains. Its stratigraphic location is not clear.

2.2. Western stratigraphy

The oldest sediments exposed on the west side of the quadrangle are axial-fluvial pebbly sands/sandstones (Tpa, QTpa). These crop out all along the west side of the quadrangle; the base of this unit is not exposed here. Morgan and Lucas (2012) report the recovery of the adult mandibles of a *Stegomastodon primitivus* from this unit by South Monticello Point. Two volcanic units intercalate with the axial-fluvial unit. At the north end of the quadrangle, the basalt of Mitchell Point (Tbm) spans the Rio Grande valley, continuing northward to an off-quad vent area. Bachman and Mehnert (1978) obtained a K-Ar age of 3.0 ± 0.3 Ma (see also Wilks and Chapin, 1997), indicating a Pliocene age for this unit. Along the east side of the Rio Grande, the basalt interfingers with axial-fluvial sediments. Along the west side, the basalt can be followed through discontinuous outcrop with fair confidence to White Cliffs, where Tbm is cut by the White Cliffs maar. Less confidently, a small, isolated, weathered outcrop of basalt to the southeast of White Cliffs may also correlate to unit Tbm. This isolated basalt occurs at the same elevation as Tbm further north, as well as at comparable elevation to the Tpal-Tpes contact to the south, possibly but not confidently relating the basalt of Mitchell Point to the eastern piedmont stratigraphy.

The second volcanic unit intercalated with QTpa is a pyroclastic interval occurring along Lakeshore Road (unit Qmps). This unit is poorly exposed, but apparently intercalates with the uppermost portion of unit QTpa. Pyroclastics appear variably reworked by alluvial processes, with common sand-sized non-volcanic detritus mixed in with ash and basaltic material. The source vent for the Qmps pyroclastics is not clear.

The western axial-fluvial unit QTpa is overlain conformably by the sand/sandstone-dominated piedmont unit Qpwf, apparently representing a progradation of the western piedmont over the axial facies. The Qpwf unit can be distinguished from the axial facies by the abundance of volcanic lithics in the sands of unit Qpwf and by the presence of bands of rhyolite-rich piedmont gravels, which increase in abundance up-section. Toward the base of Qpwf, two volcanic units intercalate. North of Alamosa Creek, pyroclastic interval Qmpp intercalates with Qpwf sediments just above the Qpwf basal contact. The Qmpp deposit here is clearly wedge-shaped, with its thickest part adjacent to the northeast side of the Monticello Point maar and the deposit thinning to a pinchout north-northeastward away from the maar. The pyroclastic interval is certainly outflow from the maar. The in-fill of the Monticello Point maar was studied by Lucas and Kietzke (1994), who found the sedimentary fill (Qmpf) to consist of finely-laminated, clayey, calcareous, fossiliferous diatomite and local fine-grained fossiliferous limestone. The sedimentary fill overlies a poorly-exposed pyroclastic diatreme (Qmpd) exposed along the southern margin of the maar.

South of Alamosa Creek, an interval of pyroclastics is exposed to the northwest of Highland Estates (Qmph) that intercalates with Qpwf and overlies Qmps. This interval pinches out in outcrop in its southeastern, northeastern, and northwestern extents, and based on this geometry a concealed vent is inferred to lie about 1 km north of Cedar Canyon, referred to here as the Cedar Canyon maar (new name). The exact location of the vent is not certain.

Qpwf is overlain conformably by a gravel/conglomerate-dominated piedmont unit, Qpwc, possibly reflecting continued progradation of the western piedmont. This unit is nearly devoid of sand/sandstone beds, consisting of predominantly rhyolite gravel-rich conglomerate. The unit has a notably clay-rich matrix, with abundant reddish coarse clay aggregates occurring as gravel coats and bridges between sand grains. This clay enrichment helps to distinguish the gravel-dominated Palomas unit from gravel-dominated post-Santa Fe Group terrace deposits. At the top of Qpwc is a well-developed soil marked by a cemented Stage III or greater carbonate horizon, indicating the top of Qpwc is the Cuchillo surface (McCraw and Love, 2012), the local top of the Santa Fe Group.

Along the southern side of Alamosa Creek, a poorly-exposed, conglomerate-dominated unit occurs (QTpwa) at comparable elevation to outcrops of QTpa and Qpwf to the south and north. The conglomerate unit is distinctly stiffer and more clay-rich than the overlying post-Santa Fe Group terrace deposits, and comparable in description to unit Qpwc, and hence interpreted to be Palomas in age, rather than post-Palomas. Its relationship to QTpa and Qpwf if not entirely clear. The only exposed contact, to the south-southeast of the Monticello Point maar, shows QTpwa overlying QTpa along a northwest-dipping contact, and hence unit QTpwa could be an inset unit reflecting a brief period of incision followed by aggradation within the Palomas sequence. However, the conglomeratic unit is here suggested to instead interfinger southward and northward with QTpa, as well as Qpwf, and possibly be the deposit of a persistent Palomas-age tributary drainage (ancestral Alamosa Creek?) that traversed the distal piedmont (Qpwf) to interact directly with the ancestral Rio Grande.

At Three Sisters Point, an additional diatreme (Ttsd) occurs with uncertain stratigraphic correlation. The diatreme crops out amongst pebbly sands reworked by Elephant Butte Lake, with no Palomas units exposed in the immediate vicinity. It is most likely, however, that the diatreme intrudes the axial-fluvial unit, QTpa. The top of the diatreme is at a comparable elevation to the top of the Black Bluffs diatreme immediately to the east, and is suggested to be of similar age.

2.3. Relating the eastern and western stratigraphies

The basalt of Mitchell Point (Tbm) potentially provides a tie between the eastern and western stratigraphies. The basalt can be mapped from The Narrows southwards along the eastern side of the inner Rio Grande valley with confidence down to the White Cliffs maar, where the basalt is cut by the maar crater and hence pre-dates the White Cliffs eruption. Further along at the same elevation, a poorly-exposed, weathered basalt crops out south-southeast of the White Cliffs maar that may be the basalt of Mitchell Point as well; this basalt clearly underlies the middle piedmont unit Tpes. Further yet to the south, the Tpal – Tpes contact is well-exposed at about the same elevation. This projection would suggest that the basalt of Mitchell Point erupted at about the stratigraphic level of the westward progradation of the eastern piedmont recorded by the Tpal – Tpes contact. Notably, the western piedmont progrades eastward somewhat stratigraphically above the eruption of the basalt of Mitchell Point, suggesting that the western piedmont prograded toward the Rio Grande somewhat after the eastern piedmont prograded. No other distinct units could be readily followed across the inner Rio Grande valley to relate the two stratigraphies.

2.4. Post-Santa Fe Group deposits

Post-Santa Fe piedmont alluvium consists of up to four mappable terrace and fan levels along smaller tributary streams (Qawy, Qawo3, Qawo2, Qawo1, Qawf3, Qawf2, Qawf1, Qaeo3, Qaeo2, Qaeo1), and up to six widespread (Qac2, Qac3, Qac4, Qac5-Qac5f, Qac6, Qacy) and two local (Qac3b, Qac5b) terrace and fan levels along Alamosa Creek. Surface soil development, where preserved, ranges from cambic (Bw) horizons overlying carbonate (Bk) horizons with Stage I morphology to argillic (Bt) horizons overlying petrocalcic (K) horizons with up to Stage III morphology. Comparing these levels of soil development to data presented by Machette (1985) suggests these surfaces range in age from Holocene to Middle Pleistocene. Deposit compositions vary with the sediment and rock types exposed upstream of each drainage; generally, western tributary terrace deposits are rich in gravels of aphanitic rhyolites with subordinate crystal-rich rhyolites and andesitic porphyries, while eastern tributary terrace deposits are rich in Paleozoic sedimentary rock types, with local Mesozoic and Precambrian rock types and trace basalts. Along the western side of the inner Rio Grande valley, many of these terrace deposits broaden into fan deposits as they enter the inner valley. Fan deposits are notably thicker than correlative terrace deposits; with some exceptions, terrace deposits are commonly <4 m thick, while correlative fan deposits are as much as 34 m thick. Terrace and fan deposits are inset upon by historic alluvium found along active tributary channels.

To the south-southeast of the Black Bluffs maar, local post-Santa Fe piedmont gravels (Qaerc) are overlain gradationally and conformably by travertine (Qtrc). The travertine unit is only found here, along a set faults in the immediate footwall of the Hot Springs fault, and their occurrence may be structurally-controlled.

Post-Santa Fe axial-fluvial terrace deposits are rare. A phreatic calcitic-cemented, pebbly, trough cross-stratified quartz sandstone unconformably overlying the Black Bluffs diatreme at its northern extent is interpreted to be a post-Santa Fe terrace deposit (unit Qrgte), as its pebble content is in stark contrast to unit Tpal, and the phreatic calcitic cement has not been found in unit Tpae. The outcrop is overlain and surrounded by loose sands and pebbles associated with Elephant Butte Lake, and the unit cannot be followed far before diving under this cover. A post-Santa Fe Group axial-fluvial terrace deposit may also exist southwest of Mitchell Point (unit Qrgt1). Here, uncemented siliceous sands and pebbly sands of the ancestral Rio Grande interfinger with uncemented piedmont gravels that are comparable to those of unit Qawf1. Such interfingering was not observed in outcrop in the Palomas section along the west side of the inner Rio Grande valley elsewhere, and hence this deposit is interpreted to be post-Santa Fe Group.

Surficial deposits of the Rio Grande floodplain and Elephant Butte Lake were mapped as interpreted from surface features apparent in multiple ages (1996, 2005, 2009, and 2014) of digital aerial imagery. Identified surface features include arcuate vegetation bands developed in meander belts and fanning distributary patterns associated with crevasse splays and deltas. In addition, a blanket of loose sands and gravels deposited by lake-reworking of underlying Palomas sediments and post-Santa Fe Group alluvium was mapped (unit Rlls14) along the inner rim of the inner Rio Grande valley where these sediments obscured the underlying geology.

3. Cretaceous geology

Upper Cretaceous strata are exposed in the southeastern corner of the quadrangle in the footwall of the Hot Springs fault and to the south of a northwest-dipping ramp structure between the Hot Springs and Hackberry faults. In anticipation of a more detailed monograph (Nelson et al., in prep), the geologic units are only reviewed here, in ascending order.

3.1. Crevasse Canyon Formation (Kcc_)

Upper Turonian through Santonian? Stages. Quartzo-feldspathic sandstones interbedded with greenish (olive-colored) mudstone and siltstone. In lower two-thirds of the formation, sandstone channel fills are subordinate to fine-grained floodplain deposits (lower unit and unit of Flying Eagle Canyon). In the upper third of the formation (Ash Canyon Member), sandstone channel fills generally predominate; however, in the upper 30 m of the formation there are subequal sandstone channel fills versus fine-grained deposits, forming a prominent strike valley. Capping a general coarsening-upward trend, pebble-conglomeratic sandstones are locally present in the upper 50-60 m of the formation. Contact with overlying McRae Formation may be conformable on this quadrangle.

3.1.1. Lower unit of the Crevasse Canyon Formation (Kccl_)

Upper Turonian or lower Coniancian Stage. White, quartz-rich, fine- to medium-grained sandstone interbedded with minor coal-bearing mudstone. Divided into three tongues, with the lower two tongues inferred to be of deltaic origin. May correlate with Gallup Sandstone, but lack of marine fossils and presence of coal beds better support correlation with the Crevasse Canyon Formation.

Lower tongue (Kccll)

White, quartz-rich, very fine- to medium-grained sandstone with minor coal-bearing mudstone. Sandstone is massive to low-angle cross-laminated to horizontal-laminated within thick, tabular beds; local lenticular, thick beds. Sand is very fine- to medium-grained (mostly fine-upper to medium-lower), subangular to subrounded, well-sorted, and composed of quartz with an estimated 15-25% feldspar, and 1-10% lithic grains. Mudstone interbeds are light- to medium-gray, massive, and contain 5-10% impure coal beds (few 10s of cm thick). Local, fine-scale interbedding of horizontal-laminated sand with 0.5-20 mm thick gray shale beds. Lacks a burrowed top (as seen in Kcclu); rather, the top is wavy- to cross-laminated. Base unexposed; suggested to be perhaps 40 m thick.

Middle tongue (Kcclm)

Gray to brownish gray, non-fissile mudstone containing 10-25% very thin-medium, lenticular beds of light gray sandstone that is mainly very fine- to fine-grained. Sandstone beds are internally laminated (horizontal-planar, wavy, or rippled). Local coal beds. 8-12 m thick.

Upper tongue (Kcclu)

White, medium-grained sandstone. Generally cross-stratified (tangential foresets up to 0.6 m tall, with local trough cross-stratification). Sand is clean, subrounded, well-sorted, and composed of quartz, minor feldspar, and 1-10% mafic grains. At top is an extensively bioturbated interval locally overlain by 0.5-1.0 m of cross-laminated sandstone. 8-12 m thick.

3.1.2. Unit of Flying Eagle Canyon (Kccf)

Local informal unit. Upper Turonian through Santonian? Stages. Olive-gray to light olive gray (5Y 4-6/2), dark grayish green (some layers are dark red, purplish gray, and ochre yellow) non-fissile claystone and siltstone [floodplain deposits] with subordinate coarser-grained sandstone [channel fill complexes] exhibiting light-gray to pale-yellow to light-olive-gray colors (5Y 7/2-3; 5Y 6/2-3; 2.5Y 6-7/2); sandstones weather to a dark brown color. Local tongues of sandstone-dominated strata, but these seldom exceed 15 m thickness. Sandstone channel-fill complexes are single- to multi-storey (seldom more than 2 storey), generally less than 6 m in composite thickness (each storey generally being 0.2-2 m thick; less commonly 2-5 m thick), and laterally continuous over distances of 20-60 m. The sandstone is mostly cross-laminated within thin to very thick, tabular to lenticular beds (medium to very thick beds commonly correspond to a single-storey channel-fill body), with tangential or planar foresets up to 20 cm thick; trough cross-lamination is commonly observed. Also horizontal-planar laminated, or 3-D ripple-laminated, or massive. Paleoflow directions from trough orientations give north to east directions. Sand is fine- to medium-grained, subangular (very minor subrounded), well sorted, and composed of quartz, 20-35% feldspar, and 1-10% lithic+mafic grains. Chlorite(?) in the sand interstices imparts the greenish color. Floodplain deposits consist of mudstone, claystone, siltstone, or very fine- to fine-grained sandstone. Mudstone and claystone are 5Y 4-6/2 (very minor 5/1-2), non-fissile, and relatively massive, but siltstone and the fine sandstone occur in very thin to medium, tabular to lenticular beds that are internally massive (commonly bioturbated) or laminated (low-angle cross-stratified, horizontal-planar, wavy, or ripplemarked); local preservation of oxidized (ferruginous) plant matter (e.g., twigs or branches). Sandstone is cemented by siliceous agents (generally no HCl effervescence). Floodplain deposits are well-consolidated but erode relatively easily. Lower contact coincides with the base of the fine-grained strata immediately overlying the highest quartzose, medium-grained sandstone of the upper tongue of the lower unit of the Crevasse Canyon Formation. The unit of Flying Eagle Canyon is non-resistant to erosion, forming slopes and valleys. 290 m thick.

3.1.3. Ash Canyon Member (Kcca)

Santonian? or Campanian? Stage. Light gray to pale yellow (10YR 7/1-2; 5Y 7/2-3) sandstone [channel-fill complexes] interbedded with subordinate mudstone and siltstone [floodplain deposits]. Sandstone layers are commonly several meters thick and are lenticular over 100-800 m lateral distances. Sandstone is extensively cross-laminated (within thick to very thick, tabular to lenticular beds), with common trough forms and tangential foresets (up to 20 cm tall); locally horizontal-planar laminated or massive. Paleoflow directions from troughs are to east-northeast. Sand is medium-grained (minor fine-grained), subangular to subrounded, well-sorted, and composed of quartz, 20-40% feldspar (the latter locally altered to a reddish color), and 1-15% mafic and lithic grains. Sandstone commonly exhibits a sparkly appearance probably due to quartz overgrowths on sand grains. Floodplain deposits consist of olive to light gray mudstone (non-fissile), siltstone, and very fine-grained sandstone. Over most of its thickness, the member coarsens upwards so that 1-2% very thin to medium lenses of pebbly sandstone are observed in the upper 50-60 m; however, in its uppermost 30 m there is more or subequal fine-grained deposits compared to sandstone -- creating a prominent strike valley north of Flying Eagle Canyon. Clasts composed of gray to black chert, quartz, quartzite, and angular argillite-siltstone rip-ups; 1-5% silicified volcanic rock (aphanitic and gray); and trace petrified wood. Pebbles are rounded, poorly sorted, and 2-30 mm long. Sandstone is well-cemented and unit typically forms ridges. Petrified wood, including logs, locally observed. Lower contact mapped at the base of the lowest laterally extensive, resistant, medium-grained sandstone bed characteristic of the Ash Canyon Member. 210-230 m thick.

3.2. McRae Formation (Kmr_)

Late Campanian? through Maastrichtian Stages, possibly as young as early Paleocene. Volcaniclastic sandstone and conglomerate derived from intermediate volcanoes, which were likely located southwest of Truth or Consequences based on coarsening trends and paleoflow data (Seager and Mack, 2003; Hunter, 1986). Three units are recognized (ascending order): Jose Creek Member, Hall Lake Member, and unit of Double Canyon. Lower 150 m of Hall Lake Member has yielded dinosaur bones of late Maastrichtian age (Lozinsky, 1985; Gillette et al., 1986; Lozinsky et al., 1984; Wolberg et al., 1986). The Jose Creek Member (80-130 m thick) is yellowish to green, contains subequal sandstone channel fills versus fine-grained floodplain deposits, has a sand fraction composed predominantly of subangular feldspar + volcanic lithics, and a volcanic gravel fraction composed of relatively monolithic, plagioclase-phyric intermediate types. The overlying Hall Lake Member is 500-730 m thick and dominated by reddish brown mudstones with subordinate volcaniclastic sandstone channel fills (locally conglomeratic) that are more heterolithic than the underlying Jose Creek Member. Reddish brown mudstones are sparse in the upper 300 m of the formation (unit of Double Canyon) and channel fills locally contain granitic clasts and arkosic sand.

3.2.1. Jose Creek Member (Kmrj)

Campanian? to Maastrichtian? Stages. Interbedded (and roughly subequal): 1) medium- to coarse-grained sandstone [channel fills] and 2) mudstone, siltstone, and very fine- to fine-grained sandstone [floodplain deposits] exhibiting an olive color. Outcrops weather to a yellowish or light gray color. The Jose Creek contains more sandstone than the overlying Hall Lake Member and reddish mudstones are rare. Scarcity of quartz and presence of notable volcanic detritus contrasts with sandstones in older Cretaceous units. Local petrified wood and fossil leaves. Channel-fills are ~0.3-1 m-thick, tabular to lenticular, and internally cross-laminated (trough forms and tangential foresets), massive, or thin to medium, tabular- to lenticular-bedded. Local subrounded very fine to very coarse pebbles composed of plagioclase-phyric, intermediate volcanic rocks (that are more monolithic than in the Hall Lake Member) or intra-formational conglomerate. Channel-fill sandstone is olive to pale olive to light olive gray (5Y 5-6/3, 6/2; 2.5-5Y 6/3; 5Y 5/3-4) or gray to brownish gray, predominantly medium- to coarse-grained (minor fine-grained and very coarse-grained), subangular, moderately sorted, and composed of feldspar (predominately plagioclase) and subordinate volcanic lithic grains. Hunter (1986) reported sandstone is composed of 56 to 76% volcanic lithic fragments, 24 to 40% feldspar, and 0 to 21% quartz. In the upper Jose Creek are layers of closely jointed siliceous rock that resembles bedded chert. In this section, Lozinsky (1985) and Seager and Mack (2003) reported shards of volcanic glass, confirming that the chert-like layers are silicified volcanic ash beds. Floodplain deposits are olive-colored (5Y 5/2; 2.5-5Y 5-6/3; 5Y 6/2-3; 2.5Y 4/2) or brownish gray in medium to thick, tabular beds that are internally massive and composed of mudstone, siltstone, very fine- to fine-grained sandstone, and clayey-silty very fine- to fine-grained sandstone; mudstone may contain minor, scattered, medium- to coarse-grained feldspar crystals. Unit coarsens upward. Lower contact mapped at base of first sandstone bed dominated by feldspar and volcanic lithics. On this quadrangle, the Jose Creek Member forms a resistant ridge north of Flying Eagle Canyon. Lower contact not well-exposed, but the transition of the upper Ash Canyon Member to finer-grained textures suggest a facies change related to a gradual shifting of depositional tracts; thus, the contact may be conformable on this quadrangle. Upper contact mapped at base of first thick, reddish brown mudstone bed of the Hall Lake Member. 80-130 m-thick.

3.2.2. Hall Lake Member (Kmrh)

Late Maastrichtian Stage. Reddish brown (dark reddish brown) to maroon to dark purplish to reddish gray (local light green), clay-dominated mudstone [floodplain deposits] interbedded with subordinate sandstone [channel fills] that extend over 20-150 m lateral distance; local sandstone-dominated tongues 30-70 m thick. Channel fills are typically single storey (1 to 3 m-thick) but locally multistorey and 4-6 m thick; these consist of medium to thick, tabular to lenticular beds that are internally massive, horizontal-planar laminated, or cross-laminated (tangential foresets, up to 20 cm tall, with local trough forms). Local conglomeratic strata typically comprised of very thin to thin, lenticular beds. Gravel consist of pebbles (0-5% cobbles) that are subrounded-rounded, moderately sorted, and composed of variable volcanic rocks (more heterolithic than the Jose Creek Member), 0-25% siliceous clasts (quartzite, chert, meta-rhyolites(?)), and 0-10% granite. Sand is pale red to reddish gray to gray to light gray, medium- to very coarse-grained, angular to subrounded, moderately to well sorted, and composed of feldspar and volcanic grains with 0-15% quartz. Based on thin-section study, Hunter (1986) reported 43 to 66% lithic grains, 13 to 30% feldspar, and 15 to 27% quartz. Sandstones are well-cemented by silica and minor calcium carbonate. Floodplain deposits are predominately mudstones but include siltstone and very fine- to fine-grained sandstones; local calcic paleosols containing carbonate stringers and vertical cylinders (after roots). Mudstones are massive and locally auto-brecciated. The Hall Lake erodes to alternating slopes and valleys of mudstone and low ridges of sandstone. The lower 150 m of the unit has yielded late Maastrichtian dinosaur fossils that include a femur of *Alamosaurus* (Lozinsky et al., 1984), a *Tyrannosaurus* jaw (Gillette et al., 1986), and various ceratopsian fossils. 500-730 m thick.

3.2.3. Unit of Double Canyon (Kmrd)

Local informal unit. Late Maastrichtian Stage, possibly earliest Paleocene. Pale brown to white to light gray (5Y 7-8/1; 2.5Y 8/1-3; 10YR-2.5Y 8/1-2) sandstone and pebbly sandstone [channel fills] interbedded with olive, greenish, or bluish-gray mudstone, siltstone, and very fine- to fine-grained sandstone [floodplain deposits]. Lower sandstone strata are predominately composed of quartz and feldspar, but the proportion of volcanic detritus increases up-section. Quartz content is higher than in Jose Creek and Hall Lake. Sandstone channel fills are thick to very thick, tabular-bedded and internally cross-laminated (tangential foresets, up to 20 cm tall, with local trough forms) or horizontal-planar laminated to medium-bedded; amalgamated channel fill complexes are as much as 7 m thick. Pebbly sandstone is commonly in very thin to medium, tabular to lenticular beds or low-angle cross-stratified. Pebbles are subangular to rounded and moderately sorted; localized presence of very minor, fine cobbles. Gravel composed of granite, intermediate volcanic rocks, fine-grained siliceous rock (chert+jasper+quartzite+aphinitic meta-rhyolite), and local intra-formational siltstone and argillite; proportion of granite decreases up-section. Sand is medium- to coarse-grained (minor fine and very coarse grains), subangular to subrounded, moderately to well sorted, and composed of feldspar, quartz, and minor volcanic lithic grains; sand becomes less arkosic and more volcanic lithic-rich up-section. Floodplain deposits include mudstone, siltstone, and very fine- to fine-grained sandstone. These rocks are mostly olive, greenish, or gray (5Y 5-6; N\6); a few layers are reddish to purplish gray. Especially in the lower Double Canyon unit, pedogenic carbonate nodules and rhizoliths are abundant. Silicified wood is common as both logs and *in situ* stumps. Local, thick intervals of silicified, white, fine tuff form ridges. Lower contact intertongues with underlying Hall Lake Member; upper contact not observed. >270 m thick.

4. Permian geology

In the far northeast of the quadrangle, the San Andres Formation occurs in fault contact with the Palomas Formation. On quad, the San Andres is medium gray, granular, and highly fractured, with thin arcuate traces of sparry calcite that may be replaced fossils; Cserna (1956) reports small gastropods in the San Andres within the Fra Cristobal Mountains. The unit was not studied in detail in this study. Nelson et al. (2012) report a maximum thickness of about 160 m in the Fra Cristobal Mountains.

5. Structure

5.1. Volcanic and intrusive structures

Four maar craters and their fills (Black Bluffs, Black Mesa, White Cliffs, and Monticello Point), two diatremes (Ocotillo and Three Sisters), and one cinder cone (Crater Hill cone) are well exposed within the quadrangle boundaries. In addition, two maar volcanoes are inferred (Rio Grande and Cedar Canyon), and additional poorly-exposed cinder and pyroclastic deposits suggest yet more vents may be present. This report will focus on the diatremes and maar craters.

This report follows the terminology advocated by White and Ross (2011). Maar volcanoes are characterized by the explosive excavation of a crater that is inset into the pre-eruption land surface. Diatremes are roughly conical-shaped (widening upwards) deposits of pyroclastic rocks found below the land surface that commonly underlie a maar volcano. Crucial components to the use of these terms, therefore, is that the diatreme and maar must be inset below surrounding pre-eruption rocks. In some on-quadrangle cases this is clear; the pyroclastics of the Ocotillo diatreme can be followed well down-section into the surrounding conglomerates of Tpem. In other cases, the surrounding wall rocks have eroded away, such as the northern and southern flanks of the Black Mesa maar. Here, the inset relationship is inferred from contact, bedding, and foliation attitudes, all of which dip radially in toward the center of the maar. Similarly, the foliations in the Three Sisters diatreme dip radially toward the center of the extent of pyroclastics, suggesting a conical inset geometry. Relict maar craters may also be suggested by evidence for pooling fluids, such as lake deposits or unusual thicknesses of basalt flows, which may have accumulated in a former closed depression. Lake sediments are found in both the Monticello Point and White Cliffs maars, locally overlying pyroclastic rocks. Fine-grained gypsiferous sediments also occur overlying pyroclastic rocks at Black Bluffs, suggesting a prior crater associated with an underlying diatreme.

The term “maar” is here only used where evidence for a topographic crater, such as lake sediments or thickened basalt flows, is present. The term “diatreme” is used in two instances. First, where pyroclastic deposits are clearly inset into surrounding pre-eruption lithologies (Ocotillo diatreme, e.g.), they are referred to as diatreme deposits. The second instance is where the pyroclastic deposits underlie maar crater fill. In these cases, it is assumed that the pyroclastics continue down beneath the level of exposure into an inset diatreme. These maar-underlying pyroclastics are commonly only poorly exposed along the rim of the maar, with foliations dipping toward the center of the maar. This pattern is interpreted to reflect subsidence of the center of the diatreme / maar crater floor down-dropping the maar-fill into the pyroclastics at the wall of the diatreme, and also causing drag folding of these wall pyroclastics; such subsidence is not uncommon (White and Ross, 2011).

Maar volcanoes are commonly surrounded by tuff rings that thin away from the maar crater. This line of evidence is used to interpret that the pyroclastics extending and thinning north-northeastward away from the Monticello Point maar (Qmpp) were ejected from that maar. Similarly, the thickness trends of the pyroclastics exposed to the northwest of Highland Estates (Qmph) suggest a concealed source vent, the inferred Cedar Canyon maar, west of the Rio Grande and north of Cedar Canyon. The pyroclastic ejecta typically fines away from the source, and in addition the depositional structures grade from high energy (scoured bed bases, swooping trough cross-stratification) to lower energy (conformable planar bedding) away from the source. The pyroclastics beneath the basalt of the Rio Grande (Qmpg) bear large bombs up to 0.7 m across and high energy depositional structures, suggesting that these pyroclastics did not erupt from the distant White Cliffs maar and instead erupted from a concealed proximal vent, the inferred Rio Grande maar. That these two concealed sources are specifically “maar” volcanoes associated with craters is not certain; however, given the presence of several well-exposed maar volcanoes in the vicinity of these concealed vents, it seems likely.

Several thin basaltic dikes intrude the Cretaceous section in the southeast of the quadrangle. East of the Black Bluffs maar, a series of commonly altered aphanitic dikes up to 2 m wide trend north-northeast to northeast in the footwall of the Hot Springs fault. Their ages are unconstrained, but likely related to the Plio-Pleistocene basaltic volcanism in the area. Further south, along the southern margin of the quadrangle, a northwest-striking dike upholds a ridge at the edge of Elephant Butte Lake. This dike is a part of a discontinuous band of basaltic dikes that Lozinsky (1985) followed well into the Elephant Butte quadrangle to the south for over 9 km south-southeastward. Aldrich et al. (1986) obtained a K-Ar age of 23.9 ± 1.2 Ma for this dike south of the quadrangle, indicated a late Oligocene age.

5.2. Tectonic structures

5.2.1. Extensional (Rio Grande rift) structures

Several north-northeast- to north-northwest-trending normal faults offset Palomas Formation strata in the quadrangle that can confidently be related to Rio Grande rift extension. Several more, mostly north-northeast trending normal faults in the Cretaceous section may also be related to the Rio Grande rift. Most of the normal faults in the Palomas section are of small offset; in fact, one fault in the northwest corner decreases in magnitude upsection into a monoclinal fold with no through-going brittle fault. Substantial Rio Grande rift structures include the Hot Springs fault, the Hackberry fault, and a ramp structure that separates the two to the south of Black Mesa.

The Hot Springs fault is here extended from Long Point Island to the south (Lozinsky, 1985) into Red Cliffs, just southeast of Black Bluffs, where the fault is exposed juxtaposing Cretaceous rocks in the footwall against the lower eastern piedmont unit Tpel in the hanging wall. The fault can be followed from here north-northeastward for ~1.7 km separating Palomas Formation and Cretaceous rocks. From here, a much smaller magnitude fault continues north-northwestward through the Palomas section, most clearly apparent in the truncation of the pyroclastic Tmpm unit. Through this latitude, the Palomas is in depositional contact with the Cretaceous, with a contact dipping gently (6-15°) generally northwestward. Dip magnitude decreases northwestward to subhorizontal again in the southern flank of Black Mesa. This area is apparently a part of a ramp structure, possibly transferring strain right-laterally to the Hackberry fault.

The Hackberry fault does not exhibit a particularly large magnitude of offset at the surface, perhaps no more than 50 m (as measured in cross-section A-A’ in the vicinity of the Ocotillo diatreme), but it is continuous from south of Black Mesa past the eastern sides of the Black Mesa maar and Ocotillo diatreme to just southwest of Crater Hill. It is also noteworthy for its apparent influence on accommodation space; in the hanging wall of the Hackberry fault, the contact between Tpel and overlying Tpal is underlain by a weak paleosol, suggesting conformity, while in the footwall the contact is highly erosive, with Tpel locally removed entirely by pre-Tpal erosion. Evidently, the Hackberry generated accommodation space for the accumulation of Palomas sediments in its hanging wall. The Hackberry ends north-northwestward in another ramp structure that separates the Hackberry from another, minor fault that continues northward to the west base of Crater Hill. This latter fault has at most ~10 m of offset, and cannot be followed with confidence much north of Crater Hill.

The Walnut Canyon fault, which lies along the west base of the Fra Cristobal Mountains, was not studied in detail in this study. However, we saw no evidence to suggest that any of the faults studied here trend toward and merge with the Walnut Canyon fault, as has been depicted in previous maps (e.g., Warren, 1978; Nelson et al., 2012). Instead, we suggest that extensional strain is transferred from the Hot Springs fault to the Walnut Canyon fault through a set of small accommodation zones and ramp structures, such as those seen south of Black Mesa and southwest of Crater Hill.

Although the Cuchillo surface (estimated age of 0.8 Ma; Mack et al., 2006) is deformed by extensional faults in the northwest of the map, we saw no evidence to suggest that any post-Santa Fe Group deposits or surfaces were deformed by faulting here.

5.2.2. Compressional (Laramide) structures

Several folds and strike-slip faults are apparent in the Cretaceous section of the quadrangle that may be the product of Laramide compression. Strike-slip offset is suggested by shallow striations on fault planes and folds adjacent to fault traces that are consistent with strike-slip drag folding. The majority of strike-slip faulting appears to occur in this quadrangle as right-lateral slip along north-northeast-trending faults, but left-lateral slip is also apparent, along north-northwest- and east-northeast-trending structures.

Laramide structures were not a focus of this study. More detailed discussions of compressional features of the area will be addressed by Nelson et al. (in prep.).

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7. Tables

Table 1: Summary of geochronologic data for units on the Black Bluffs 7.5' quadrangle

Unit	Age[1] (Ma)	±2σ[2]	Type[3]	Ref.[4]	Latitude	Longitude	Comments
Qbch	2.15	0.04	Ar-Ar	P16	33°21.38'N	107°08.06'W	New age
Qbwc	2.50	0.06	Ar-Ar	P16	33°19.69'N	107°07.98'W	New age
Tbm	3.0	0.3	K-Ar	BM78	33°21'N	107°11'W	
Tbd	23.9	1.2*	K-Ar	A86	33°11.4'N	107°08.4'W	

1: Age as published. No attempt made to normalize values.

2: Uncertainty as published. An asterix (*) indicates that the published uncertainty does not specify 1σ or 2σ.

3: Ar-Ar: 40Ar/39Ar crystallization age.

4: BM78 - Bachman and Mehnert, 1978; A86 - Aldrich et al., 1986; P16 - Peters, 2016, and this report