Geologic Map of the Bread Springs 7.5-Minute Quadrangle, McKinley County, New Mexico

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September, 2024

New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 305

Scale 1:24,000

https://doi.org/10.58799/OF-GM-305

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program under STATEMAP award number G22AC00601, 2022. Additional support was made possible by the 2023 Technology Enhancement Fund provided by the New Mexico Higher Education Department. Funding is administered by the New Mexico Bureau of Geology and Mineral Resources (Dr. Nelia W. Dunbar, Director and State Geologist (2023); Dr. J. Michael Timmons, Director and State Geologist (2024); Dr. Matthew J. Zimmerer, Geologic Mapping Program Manager).

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EXECUTIVE SUMMARY

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Location and Access

The Bread Springs 7.5-minute quadrangle is located in McKinley County in west-central New Mexico. The southern portion of the city of Gallup, the county seat, is located along the northernmost section of the quadrangle. Located on the high-elevation southeastern Colorado Plateau, the area experiences cool to cold winters with occasional snowfall, cool spring and fall temperatures with generally dry conditions, and mild to hot summers with monsoon moisture from July through September. The Gallup-area climate is designated by the Köppen climate classification as a cold semi-arid climate (Bsk). The area is rugged and generally remote. Defining geographic features include The Hogback along the eastern boundary of the quadrangle, a north-south to northwest-southeast trending ridge that comprises the western margin of the Zuni Mountains, an unnamed high-elevation ridge across virtually the entire quadrangle from northwest to southeast, and the high-elevation plateau of the southern map area.

New Mexico State Route 602, located all along the western part of the map area, is the only main highway located in the quadrangle. Other paved access roads include Blue Medicine Well Road/Navajo Service Route 7047, Bread Springs Road/Navajo Service Route 74, and Rodeo Road. There are numerous dirt and tertiary roads throughout the Bread Springs 7.5-minute quadrangle. County Road 16/Indian Service Route 7048 gives access to the northeast part of the map area, and Bitter Spring Road gives access to the southwest part of the map area.

The area is largely rural and located in the Navajo Nation (Figure 1); the majority of the Bread Springs chapter and part of the Red Rock chapter lie within the quadrangle. Permission is required to access parts of Navajo Nation land. Numerous private residences are located throughout the map area, and privacy must be respected. Private property and locked gates make access to the north-central part of the map area difficult without permission. There are small parcels of State and Bureau of Land Management land, and the southeastern corner of the map is part of the Cibola National Forest (Mt. Taylor Ranger District). Old coal mines are located in the northern part of the map and access is generally restricted. Lastly, a thin sliver along the northeastern map boundary is part of the Fort Wingate Army Depot operated by the Department of Defense. Access to Fort Wingate was not able to be acquired. Further, numerous unexploded ordinances (UXO's) may be present along The Hogback within and near these grounds, and extreme caution is suggested for anyone who conducts permitted reconnaissance of the area.

Note: it is the responsibility of the map user to research and request access permissions. Privacy must be respected, and proper permits must be acquired to conduct any type of work.

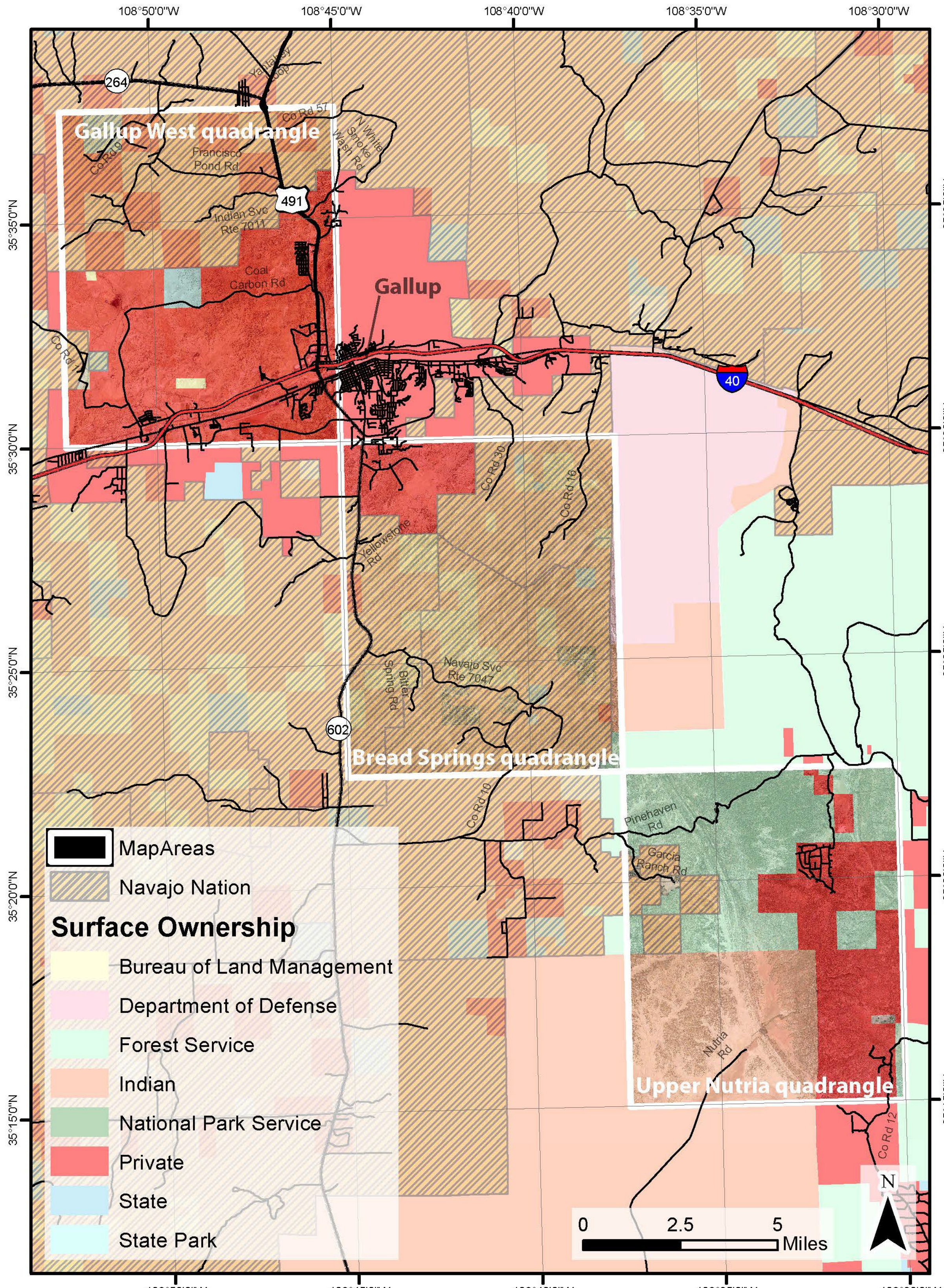

FIGURE 1— Property ownership in and around the Bread Springs 7.5-minute quadrangle and Gallup area.

FIGURE 2—Screenshot from the National Geologic Map Database (NGMDB) website showing mapped 1:24,000 scale quadrangles around the Gallup area. Bread Springs 7.5-minute quadrangle (outlined in bold red) represents a gap in mapping.

Methods for Geologic Mapping

To date, geologic mapping of this quadrangle has not been greater than 1:125,000 scale (FIGURE 2); completion of this geologic map fills a gap of scale 1:24,000 geologic maps in the Gallup area, with completion of the Gallup West and Upper Nutria quadrangles to the northwest and southeast, respectively, also concurrently in progress (FIGURE 1: Aby, in press; Riesterer and Drakos, in press). A combination of digital and field mapping techniques were incorporated to map the area. Digital mapping was conducted using NAIP aerial imagery and a lidar-derived, 1-meter-resolution DEM and hillshade. Initial reconnaissance mapping was done digitally to outline major washes and alluvium-filled drainages; these were later field-checked across the map where access could be made. Field mapping was conducted using traditional techniques with lines drawn on paper field maps, a Garmin GPSMap 64ST GPS unit to mark station locations, and notes handwritten in a field notebook. Field mapping was conducted on 1:18,000 scale base maps. Structural, paleoflow, and bedding measurements were taken with a Brunton Geo Transit; the digital app FieldMOVE Clino was utilized in certain situations for data collection (e.g., taking many measurements to calculate an average).

Unit thicknesses were estimated from mapped contacts and dip measurements in those general areas. Most thicknesses were estimated in areas where dips were consistent and not varied over short/long distances (e.g., The Hogback) in order to ensure a more accurate estimate.

Cross sections were constructed using mapped contacts and orientation measurements; constant bed thickness was used in all sections. Topographic profiles were constructed by the New Mexico Bureau of Geology and Mineral Resources GIS Services Program in ArcGIS for cross-section lines designated by the author. These profiles were populated with geologic map information such as contacts and faults boundaries. Thickness estimates for units not found on the Bread Springs 7.5-minute quadrangle (i.e., units older than the Triassic Petrified Forest Formation) were estimated using thicknesses presented in Anderson et al.'s (1998) map of the Fort Wingate quadrangle immediately east of the map. Based on existing oil and gas wells in the Gallup area, accessed via the New Mexico Oil Conservation Commission (https://www.emnrd.nm.gov/ocd/occ-info/) and U.S. Geological Core Research Center online database (https://www.usgs.gov/core-research-center), a simplifying assumption was made that pre-Permian rocks (Pennsylvanian and Mississippian, specifically) were not present in the subsurface, and that Permian Abo Formation rested non-conformably on Precambrian rock. Sections were hand drawn, scanned, and then digitized in ArcGIS.

Geology

Paleozoic and Mesozoic Stratigraphy

Triassic through Cretaceous sedimentary rocks are located within the Bread Springs 7.5-minute quadrangle. The oldest rocks are the Triassic Chinle Group (Painted Desert Member of the Petrified Forest Formation, using the nomenclature of Anderson et al., 1998) in the northeast part of the map along The Hogback's eastern edge. Approaching The Hogback, the youngest Triassic unit is the Owl Rock Formation, followed by Jurassic sedimentary rocks. As mapped, these Jurassic rocks include (from oldest to youngest) the Entrada Sandstone, Todilto Limestone, Zuni Sandstone, and Morrison Formation. Designation of the Zuni Sandstone as a mapping unit is the choice of the author due to its distinct "candy-striped" facies and the use of that mapped unit name in the Fort Wingate quadrangle to the east (Anderson et al., 1998). Use of the term Zuni Sandstone is not in accord with recent suggestions by Cather (2021), who restricts the term only for areas to the southwest near Zuni Pueblo where the Todilto Limestone pinches out and Entrada Sandstone is indistinguishable from upper sandstone facies.

Late Cretaceous strata make up two parallel ridges to form The Hogback. On the eastern ridge, these strata are mapped from oldest to youngest as the Dakota Sandstone, Whitewater Arroyo Tongue of the Mancos Shale, and the Twowells Tongue of the Dakota Sandstone, the latter of which makes the face of the eastern ridge. A strike valley of Mancos Shale separates the eastern ridge from the western ridge. The western ridge of The Hogback consists of the Gallup Sandstone, which includes (from top to bottom) the D, E, and F sandstones according to the nomenclature of Molenaar, 1973 (FIGURE 3); these sandstones are separated by small strike valleys of shale and coal atop the western ridge. The D sandstone of the Gallup Sandstone largely makes up The Hogback's western ridge face, but in places the overlying Crevasse Canyon Formation is exposed.

As mapped, the Crevasse Canyon Formation in the Bread Springs 7.5-minute quadrangle includes the Torrivio Sandstone Member overlain by the Dilco Member.

FIGURE 3—Annotated image (looking northeast) showing part of the Cretaceous stratigraphy in the map area. Note the slump block at the center-right of the image.

The Dilco Member of the Crevasse Canyon Formation is the dominant unit exposed in the northern part of the map area, west of The Hogback and north of the dominant northwest-southeast ridge. Dilco facies exhibit an olive-drab to gray appearance and are typically fine-grained with carbonaceous shales and coal beds (some of which exhibit petrified wood). A distinct white-brown, medium-bedded sandstone is exposed in the map area, notably near The Hogback just north of County Road 16. This bed appears consistent stratigraphically in the northern part of the quadrangle and is referred to as Kcdikb (FIGURE 4) in this mapping.

FIGURE 4—(Left and Right) Dilco Member of Crevasse Canyon Formation. Both photos show top-capping Kcdikb that is mapped herein; photo at right shows characteristic fine-grained nature of Dilco Member.

The Bartlett Member of the Crevasse Canyon Formation is mapped across the entire quadrangle from northwest to southeast at/near the base of the high northwest–southeast ridge across the map area. A type section of the Bartlett Member in stratigraphic contact with the underlying Dilco Member is exposed at Purty Rock (UTM 12N 692010m E, 3923044m N) in the Manuelito quadrangle to the west (Anderson, 1991). The thick-bedded, bulbous weathered sandstone of the Bartlett Member is in stark contrast to the thin- to medium-bedded, fine-grained, olive-drab, coal-rich, and channel-body sandstones of the underlying Dilco Member.

Overlying the Bartlett Member is a combined unit for the Crevasse Canyon and Menefee Formations known as the Crevasse Canyon Formation Gibson Coal Member and Menefee Formation Cleary Coal Member, mapped simply as Kmfg (e.g., Figs. 5, 6) following 1:24,000 and 1:100,000 scale mapping north of the Bread Springs quadrangle. This designation is required in the Gallup area as the Point Lookout Sandstone, a stratigraphic marker that separates Gibson and Cleary coal members of the Crevasse Canyon and Menefee Formations, is observed to pinch out northeast of Gallup; offering no stratigraphic marker to separate these two units that are interpreted to have the same, continuous depositional environment (e.g., Dillinger, 1990) and consequently similar visual appearance. Kmfg is the dominant unit, covering large portions of the southern two-thirds of the map, and consists of a lower silty facies and upper thick-bedded sandstone facies. In many places, Kmfg facies appear similar to Dilco Member given both display olive-drab shales, but Kmfg is distinct from Dilco by the presence of silver-blue shales (in addition to olive-drab shales) and apparent tabular, thick-bedded sandstone bodies. Channel body sandstones are abundant in Kmfg, too, however. The contact between the Dilco and Bartlett members is commonly sharp. However, the contact between the Bartlett Member and Kmfg is commonly approximate to inferred, as silty facies lacking coal can be lumped into the Bartlett Member (originally defined as the Bartlett Barren Member by Sears [1925] for its lack of coals). The northwest part of the map area, accessed by Catalpa Wash Road, has the clearest exposures of distinctions between Dilco, Bartlett, and Kmfg as they are mapped in the Bread Springs 7.5-minute quadrangle.

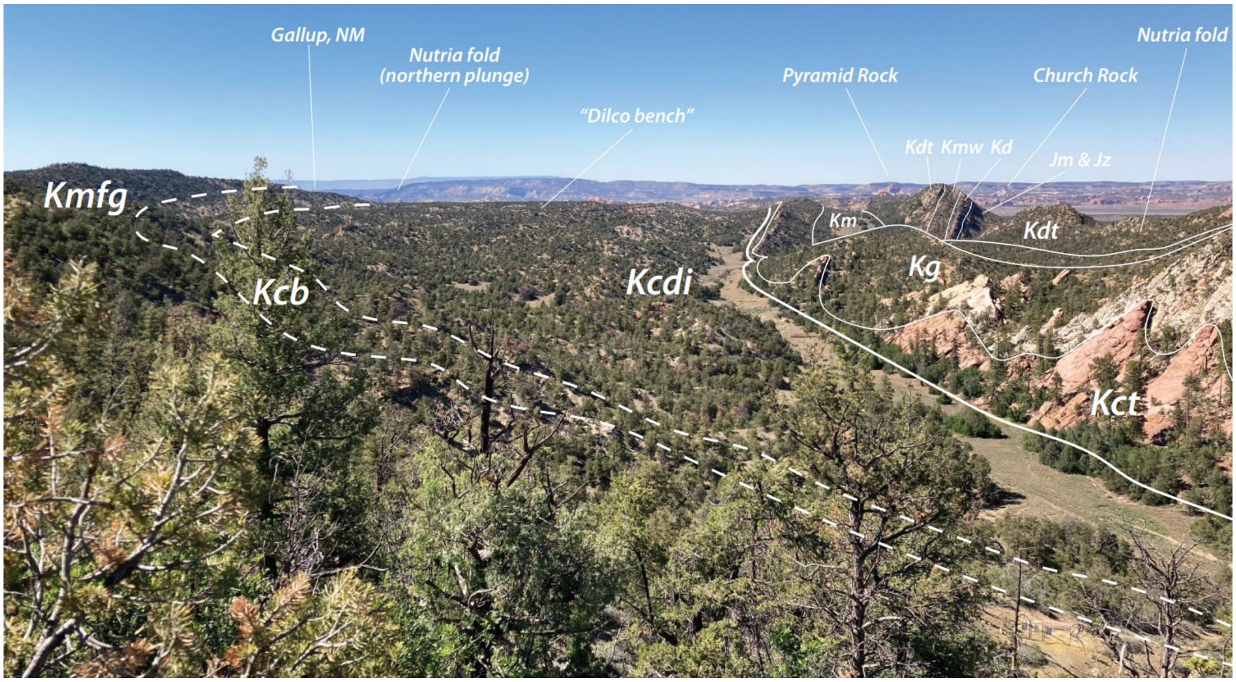

FIGURE 5—Annotated image (looking north) near Fenced-Up Horse Valley showing nearly the entire Cretaceous section as mapped on the quadrangle. Nutria fold at right exhibits a northerly plunge toward and past the town of Gallup, NM.

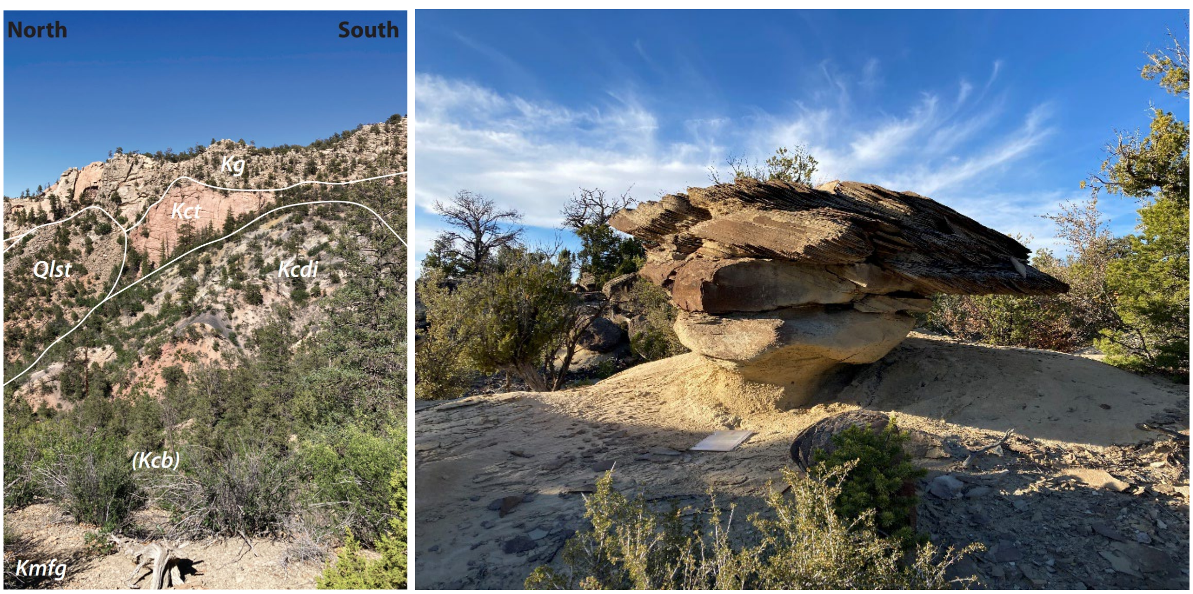

FIGURE 6—(Left) Annotated image showing Kg through Kmfg units, and landslide material. (Right) Small hoodoo shows characteristic facies of Kmfg, with rusty-brown concretionary sandstones that are heavily cross-bedded and light-tan sandstone.

A small portion of Allison Member of the Menefee Formation is mapped in the northwest extreme of the map area and is the youngest unit on the map that is certainly Late Cretaceous. In the southeast part of the map area, a sandstone-dominated package is mapped but its age is not certainly Cretaceous or Tertiary. This unit, in places, resembles the Miocene Bidahochi Formation (discussed below), but in other places its facies consist of light-colored, medium- to thick-bedded sandstones capped by iron-rich concretionary sandstones that are akin to the Menefee Formation. A further distinction is the presence of purple shale layers. At present, the age of this unit is unknown and requires further work, but the unit is positively inset into Kmfg and in one location (UTM 12N 711206m E, 3917540m N) exhibits an impressive stacked channel complex in a roadcut along Bread Springs Road.

To the author's knowledge, this map is the first attempt in the Gallup area to break out members of the Crevasse Canyon and Menefee Formations at 1:24,000 scale. Across the map area, distinct facies appear laterally continuous and traceable. This map is also the first to bring the combined Crevasse Canyon/Menefee formations unit, Kmfg, this far south into the Gallup Sag/Zuni Basin, the topographic and geologic depression in west-central New Mexico between the Zuni and Defiance Mountains.

Structure

Subtle but significant faults and folds are located throughout the quadrangle. Most structures are the result of Late Cretaceous–Paleogene Laramide tectonism, while some structures appear younger but of unknown age. Major structures have been mapped at scale 1:125,000 and smaller; however, this updated large-scale geologic mapping has discovered subtle intra-basin folding and low-displacement faults not previously recognized.

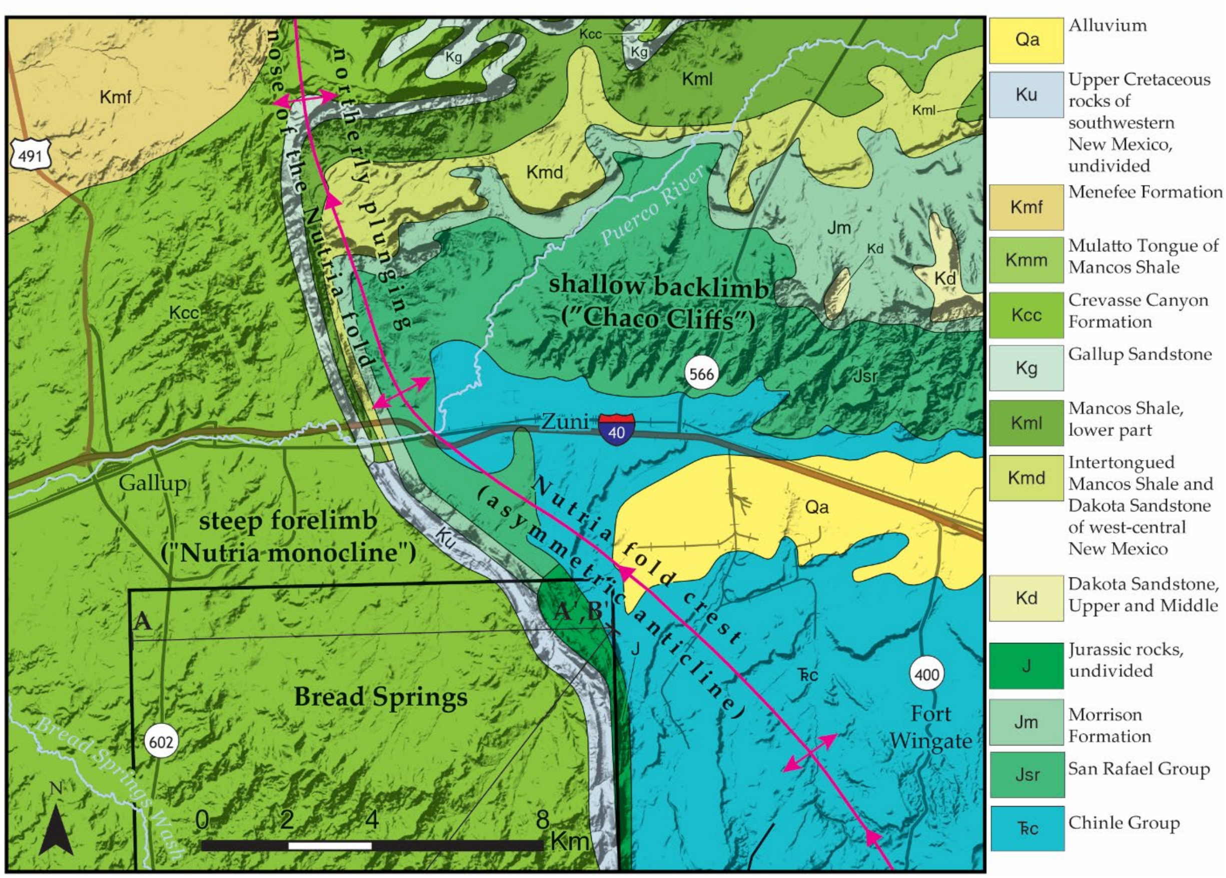

FIGURE 7—Regional map displaying the generalized extent and scale of the Nutria fold in relation to the Bread Springs quadrangle. Geology from the Geologic Map of New Mexico OFGM-304. Unit descriptions can either be found in this publication or from the geologic map-unit descriptions in OFGM-304. Note: Kmf and Kcc are mapped differently on the 1:500,000 state geologic map, and new Bread Springs mapping pushes Kmf further to the south.

Folding

Major structures are the Nutria fold and the Allison syncline. The Nutria fold makes up the western margin of the Zuni Mountains, a Laramide arch that uplifted via ENE-WSW shortening ca. 80–45 million years ago (Thacker, 2020; Thacker et al., 2021) (FIGURE 7). Commonly referred to singularly as the Nutria Monocline, the Nutria fold is the forelimb of an asymmetric anticlinal system that makes up the Zuni arch, which plunges northerly, east of Gallup; the Chaco Cliffs, north of U.S. Interstate-40, comprise the shallow-dipping backlimb of the anticline. Dips along the Nutria fold are moderate (≈30°) to steep (≥60°), and the fold trace is sinuous from northwest–southeast, to north–south, to again northwest–southeast. The Allison syncline is a broad wavelength, gentle to open, but regionally significant fold that represents the axis of the Gallup sag/Zuni basin. Physiographically, and perhaps structurally, the Allison syncline represents an embayment of the San Juan Basin into the Gallup area. The trend of the fold axis is sinuous, entering the map area coincident with Bread Springs Wash, veering southeasterly, then south–southeasterly near the confluence of Pine Tree Wash with Bread Springs Wash.

Previously mapped but lower magnitude folds include the Gallup syncline and Gallup anticline. The Gallup anticline is asymmetric to the west and doubly plunging. It is northerly plunging in the Gallup East quadrangle (Green and Jackson, 1976; Dillinger, 1990), north of the map area, and south-plunging in the Bread Springs 7.5-minute quadrangle; its crest located just north of the map area. As mapped, the fold axis trends north–northwest, veers east–southeast, then curves to northwest coincident with the fold pattern becoming monoclinal at a structural bench near Sundance Wash in the northeast part of the map area. This structural bench appears to have formed as the Nutria fold bifurcated into two structures and is the cause of the large spatial exposure of Dilco Member in the northern part of the map.

Folds that have not been previously mapped include the Bááháálí syncline and Bááháálí anticline. Other small, subtle folds include a small anticline-syncline-anticline trio on the southwest limb of the Allison syncline in the southwest part of the map area; these folds were not mapped in detail but may represent a left-stepping en échelon system. Although subtle, the Bááháálí anticline and syncline pair are significant to the map area and sub-regionally. The major northwest–southeast ridge across the entire map area is largely coincident with the Bááháálí syncline. The Bááháálí anticline is situated on the northeast flank of the Allison syncline and is doubly plunging. The structurally highest portion of the fold is located just south of the central part of the map (approximately UTM 12N 709738m E, 3922802m N), where Bartlett Member of the Crevasse Canyon Formation is interpreted due to a lack of coals in the stratigraphy at wash level. Northwest of this exposure, the plunge is northwest; southeast of this exposure the plunge is southeast. Both the Bááháálí syncline and anticline die out in the southeast part of the map. In the Vanderwagen and Upper Nutria quadrangles to the south and southeast, it is likely that the Allison syncline and Nutria fold become an anticline-syncline pair, but in the Bread Springs 7.5-minute quadrangle, bifurcation of the range front structural system causes intra-basin complexity. Bifurcation is interpreted to be the result of blind thrusts in the subsurface, as shown on the A–A′ and B–B′ cross sections, that acted as forethrusts to the Zuni arch, perhaps as an imbricate fan system. This same imbricate fan structural framework may hold true north of the map area, where it is speculated that a "Gallup thrust" may core the Gallup anticline, and a "Torrivio thrust" may core the Torrivio anticline further west, but this hypothesis requires further analysis.

FIGURE 8— Panoramic photo taken west-southwest of Bread Springs Chapter House showing subtle Laramide folding. Photo is sub-parallel to the B–B′ cross section line.

<u>Faulting</u>

Faults in the map area (FIGURES. 9–11) are difficult to discern due to the complex, discontinuous sandstone and shale fluvial facies of Kmfg. Therefore, more faults are certainly present than are mapped. Three previously unidentified normal fault populations were discovered:

(1) Northeast-striking, up to 10-m-throw normal faults are sub-perpendicular to fold axes and do not cut overlying Late Cretaceous units (FIGURE 9). Given this relationship, these faults are suggested to have formed syndepositionally (ca. 85 Ma). Shear-sense criteria along the fault planes suggest dip-slip displacement (FIGURE 11). A peculiar observation of the fault planes is their appearance, which crudely resemble flute casts that form during soft-sediment transport, further suggesting the faults were syndepositional and formed prior to full lithification (note: it is not being suggested these features are flute casts; only that their appearance resembles them). A questionable inferred fault of this orientation is found at Peretti Canyon (UTM 12N 709472m E, 3926330m N), where a distinct northeast–southwest physiographic lineament is observed through a small saddle in the dominant ridgeline. Inspection of this area yielded no obvious fault features. However, two float pieces of rock exhibited milky-white veins (presumed calcite) not commonly observed in the Kmfg facies, and a thick-bedded sandstone appeared to be discontinuous across the small valley, possibly suggesting a fault there. It is uncertain if this discontinuous, thick-bedded sandstone represents a channel margin or fault.

FIGURE 9—Northeast-striking faults in the map area that cut Kmfg. Note in both images how the orange-tan sandstone capping outcrops is not cut by faulting, suggesting synsedimentary deformation during (or shortly after) Kmfg deposition.

(2) A south–southwest-striking normal fault (or faults) of unknown throw and age is proximal to The Hogback. One fault was positively identified at UTM 12N 715479m E, 3920571m N; the second fault is inferred based on alignment/barbs of wash drainages and apparent vertical offset of sandstone beds across a small valley. The positively identified fault also exhibits a soft sediment appearance to the fault plane and largely dip-slip motion from shear sense criteria on the fault face.

(3) A northwest-striking 10–20 m-throw normal fault zone of unknown age near Gallup cuts Late Cretaceous strata near and across NM-602 (Figure 10). This fault zone may be the youngest in the map area; obvious hill slope changes are coincident along it, suggesting motion could have been Late Cenozoic, but Quaternary alluvium in washes is not discernibly displaced, suggesting that motion has not occurred during the Holocene. These inferences are not robust, however, and trenching the fault may prove useful. Where observed, the fault plane is planar (not appearing soft sediment) and exhibits dip-slip shear-sense criteria (Figure 11). The fault zone is largely down-to-the-northeast, but one portion exhibits an antithetic fault that forms a horst block for short-strike length at UTM 12N 705597m E, 3929307m N. The southeast extent of the fault zone appears to die out along strike; the northwest extent of the fault zone curves northerly and appears to displace Kmfg with visible slight differences in the Kmfg facies across the along-strike continuation of the fault.

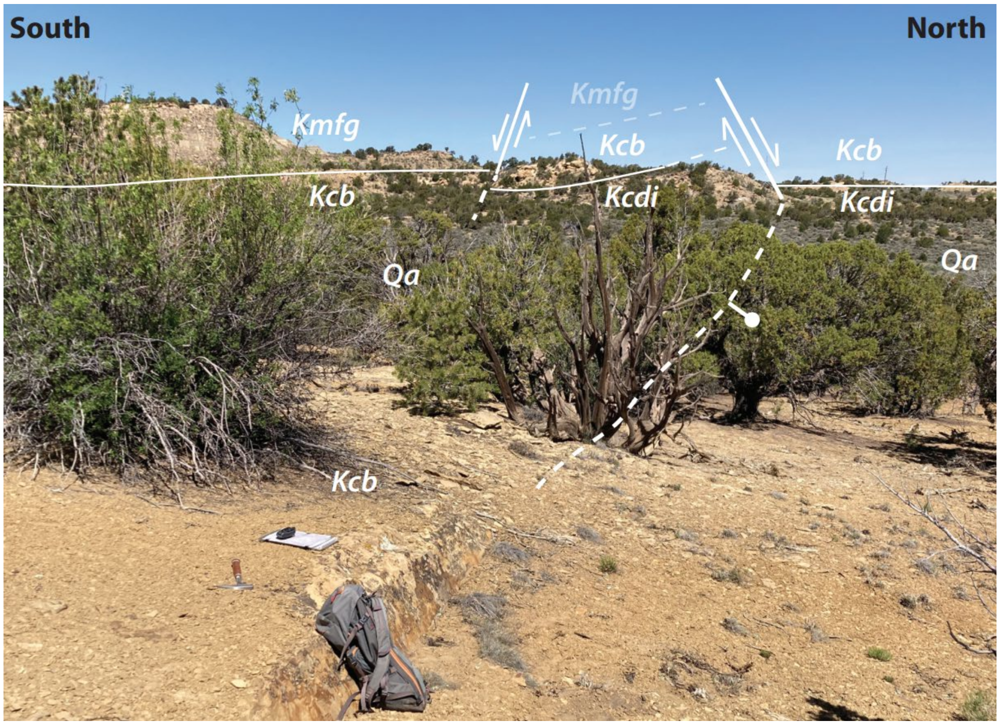

FIGURE 10—Annotated image showing fault zone at the northwest corner of map area in Catalpa Wash subdivision near the town of Gallup, NM. A backpack is on the fault surface with exposed slickenlines.

FIGURE 11—Equal-area lower hemisphere stereonets showing different fault populations mapped in the Bread Springs quadrangle and their respective shear sense criteria (slickenlines and slip directions); arrows show direction of hanging wall motion.

Cenozoic Deposits and Erosion

Bidahochi Formation is present in the southwest corner of the map. An unpublished date from a sample west of the Bread Springs quadrangle suggests the age of this unit is Middle Miocene (Steve Cather, personal communication). In the quadrangle, Bidahochi Formation covers underlying Cretaceous units, its base at ≈2210 m elevation; this lower contact may grade higher eastward, toward the Zuni Mountains, suggesting post-Cretaceous uplift of the Zuni Mountains area (McCann, 1938). Much of the Bidahochi surface appears to be reworked into eolian sand.

Where outcrop is present, the formation is reddish to peach-colored, fine-grained, moderately to well-sorted, quartz-rich sands, suggesting a medial to proximal source. A sandstone bed and a very friable chalk-like layer are found within 5 m of the base of the contact. Reddish hues in Kmfg strata make mapping between Bidahochi and Kmfg difficult in the southwest part of the map area, but distinct differences are observable in the field to distinguish these units (see Description of Map Units).

As mentioned above, the southeast part of the map area contains a sedimentary unit that is not currently easily distinguishable from the Menefee Formation or Bidahochi Formation. The unit clearly cuts and is inset into Kmfg, and exhibits channel body sandstones and stacked multi-story channels. Sandstones are reddish to peach-colored, similar to the Bidahochi Formation, and are commonly in stark contrast to underlying/nearby olive-drab shales and white, fine-grained sandstones that are assuredly Cretaceous. There is also a purple shale that is not commonly seen in the map area. Unlike Bidahochi Formation, and more akin to Kmfg, however, are rust brown-colored concretionary sandstones that appear to cap the unit in places; a facies more consistent with Late Cretaceous sedimentation. Leaf fossils were found in the channel body sandstone at UTM 12N 711206m E, 3917540m N but these have not yet been identified. Currently, the unit is thought to be a Menefee channel body, given the rust-colored concretionary sandstones, but it is not yet certain and the unit could represent an upstream facies of the Bidahochi Formation.

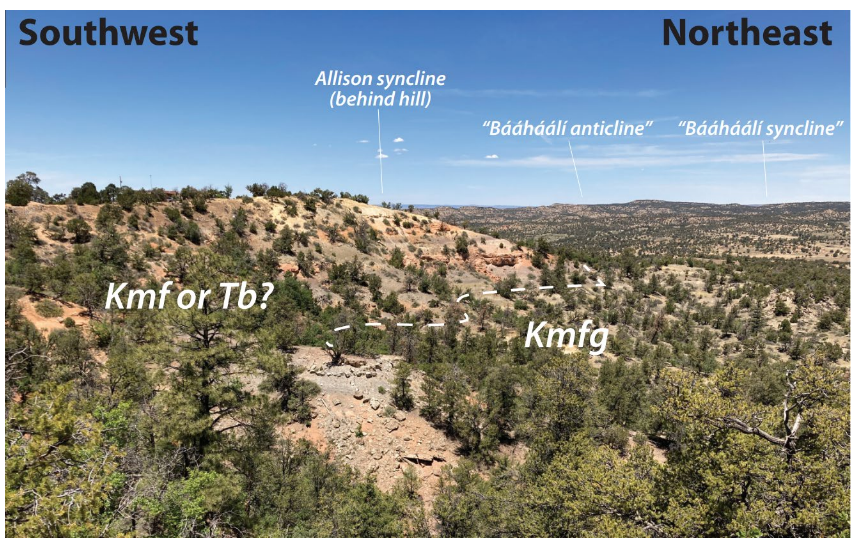

FIGURE 12—Annotated image showing questionable unit in southeast corner of map area.

Near the headwater reaches of Bread Springs wash, perched gravel deposits are found on the south side of the wash above the modern drainage. The age of these deposits is currently unknown, but their elevation and composition warrant their being mapped as Quaternary–Tertiary. These gravels define an upslope surface from ≈2,230–2,300 m elevation eastward toward the Zuni Mountains. Grain-size of the gravels increases eastward from pebble to cobble size in the furthest west outcrop at UTM 12N 714155m E, 3919956m N to cobble to boulder (1 m across) size at the furthest east outcrop in the map area at UTM 12N 715638m E, 3919714m N. Clast varieties appear to become less diverse toward the east, as well. Western exposures consist of a fair amount of orange, fine-grained sandstone, interpreted as Permian Glorieta Sandstone, as well as white sandstones that are likely Dakota and/or Gallup sandstones, black-brown ("chocolate") chert clasts likely from the Dilco Member of the Crevasse Canyon Formation, rounded quartz pebbles, and a white-purple rhyolite of unknown origin. The easternmost outcrop consists dominantly of Permian Glorieta sandstone, as well as lesser amounts of the white-purple rhyolite and minor other clasts. In all outcrops of the perched gravel, positively identifiable Triassic and Jurassic rocks are not observed; only Permian, volcanic, and likely Cretaceous. Anderson et al. (1998) mapped a Laramide fault, the Stinking Springs fault, to the east in the Fort Wingate quadrangle that brings up a thrust sheet of Permian Glorieta Sandstone over Triassic rocks. It is presumed that the provenance of these gravels is the Zuni Mountains from the Stinking Springs thrust sheet. The white-purple rhyolite is yet unknown, but it is hypothesized to be from the Mogollon-Datil Volcanic Field. If so, this would suggest that the drainage was connected to Mogollon-Datil deposits and/or the volcanic field, extending the reach of the drainage system ≈100 km further southeast.

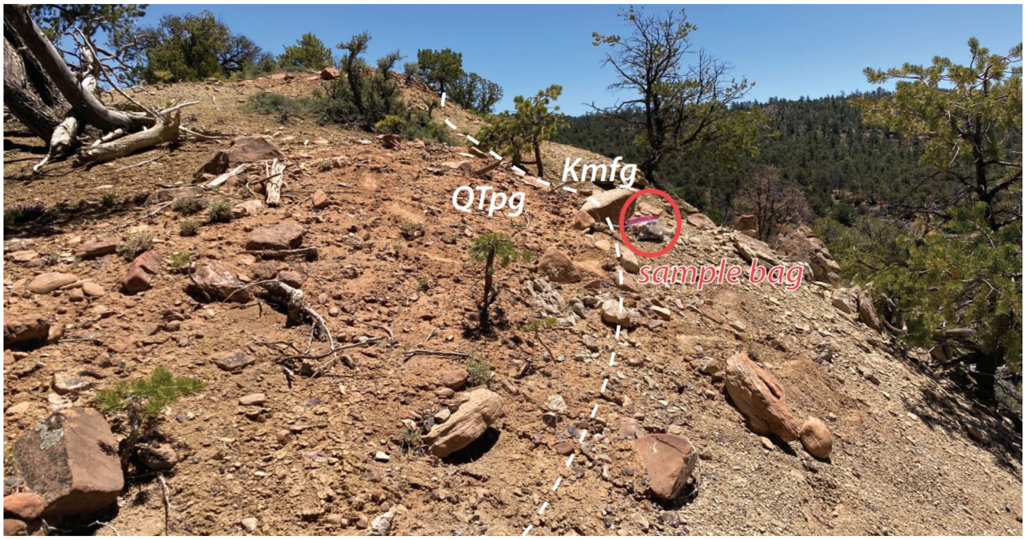

FIGURE 13—Perched gravel deposit on top of Kmfg in the southeast corner of the map area. One gallon sample bag shows scale.

Eolian sand deposits are found across the map area. Generally, these deposits display two characteristics: reddish hues in flat areas, and light-colored deposits, occasionally in up to 1 m tall coppice dune form. Distinction between these two types was not conducted during the mapping. Analysis of paleo-wind directions was neither conducted, nor were obvious features to distinguish wind direction readily observed. Age of the deposits is presumed Quaternary, but red-colored eolian sand may be older and therefore could be Quaternary–Tertiary.

Mass-wasting features and alluvial deposits appear inextricably linked in the northeast part of the map area in strike valleys of The Hogback. Slump and/or topple features appear to have impounded strike valleys at a prior incision history, and aggraded material to a stable surface high above the modern Qa fill and active arroyo incision. This is observed in at least two locations: UTM 12N 713057m E, 3930982m N and UTM 12N 715299m E, 3927343m N.

Modern drainages have defined six map-scale watersheds in the quadrangle. All of these drainages flow into the Puerco River, the major drainage of the Gallup area. Bread Springs Wash is the dominant drainage and a defining feature of the Bread Springs 7.5-minute quadrangle, located from the southern to western part of the map area. Pine Tree Wash is the second major drainage and feeds into Bread Springs Wash, in the southwest part of the map. The northern part of the map is drained, from west to east, by the Catalpa Canyon, Peretti Canyon, and Sundance washes, and a minor wash known as Fenced-Up Horse Valley, drains the east-central extreme of the map area. Drainage orientations appear to be structurally controlled, with a pervasive northeast trend in the western to southern part of the map. Northeast trends may be the result of topographic lows within the Allison syncline, and/or unmapped northeast-striking faults (mentioned above). Modern washes appear to be actively incising Qa fill, and alongside perched alluvium impounded behind mass wasting debris, the map area suggests at least two episodes of incision with one intervening period of aggradation during the Quaternary or Quaternary–Tertiary. Hypothetically, this timeline may represent an initial incision episode to destabilize hillslopes to cause mass wasting, followed by one (or more) aggradation events to deposit Qa and Qap, and a current ongoing episode of incision.

Hazards

Arroyo Incision: Modern drainages are incising deeply into Quaternary alluvium, sometimes as much as 30–60 feet (10–20 m) like at UTM 12S 713980m E, 3929212m N along County Road 16, in the northeast part of the map area. Incision appears decadal-scale, as Google Earth historical imagery of this same area shows headwater incision of the Sundance Wash as much as 0.25–0.5 km since 2005. Also apparent in this historical imagery is the required movement of the road during incision. Flash flood events would provide necessary conditions to increase incision, and are of concern to major and tertiary roadways (e.g., Navajo Service Routes and NM-602).

Mass Wasting: Mass wasting in strike valleys of Mancos Shale and Dilco Member are described above and are common in over-steepened, high-dip areas of The Hogback. Map-scale landslides of this nature are likely uncommon, but small slide and topple features are certainly possible in the map area where fine-grained units are exposed. Furthermore, the interbedded shale-sandstone fluvial deposits of Kmfg would be susceptible to mass wasting.

Faulting/Seismicity: No faults mapped in the study area appear to have had historical (less than thousands of years) slip. Fault populations one and two presented above (northeast and south-southwest striking) appear to be Late Cretaceous in age, as these faults appear to have formed syndepositionally and are covered by more Late Cretaceous strata. The northwest-striking fault in the northwest part of the map (south of Gallup) is of uncertain age, but given its geomorphic appearance may be geologically recent (Quaternary–Tertiary); the strike of this fault zone is also dissimilar to other faults mapped in the Bread Springs quadrangle, suggesting a unique slip history. It does not appear likely that the fault is active, but more work is warranted to investigate seismic potential.

Abandoned Coal Mines: Old coal mines are found at upstream portions of the Catalpa Canyon and Sundance drainages. An attempt to study groundwater quality downstream from these abandoned mines was not conducted in this study. Surficial and mass wasting processes as well as extensive surface water runoff and soil erosion associated with these anthropogenically stripped areas are possible.

Acknowledgments

Fieldwork on the Navajo Nation was conducted under a Permit from the Navajo Nation Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for and receive a Permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 86515 and Telephone No. (928) 871-6587.

In addition to this permit, numerous landowners were generous in providing access to and across their land for the field mapping. Thacker wishes to acknowledge the Bread Springs chapter manager, Gloria M. Skeet, for such permission that was crucial for mapping the southeastern corner of the map. Naming of the newly mapped folds in the quadrangle as Bááháálí anticline and Bááháálí syncline was approved by the Bread Springs chapter officers, a request from the author that was facilitated by Gloria Skeet. Thacker wishes to thank the chapter officials and Gloria for their assistance in this process.

Description of Map Units

CENOZOIC

Quaternary

Anthropogenic Units

afd—Anthropogenic fill, excavated, and disturbed ground

Fill along roadways, across drainages, and excavated and disturbed areas from past coal mining.

ad—Anthropogenic dam and/or berm

Artificial fill (likely locally derived and excavated) in arroyos to make stock ponds and/or ponds for mining operations.

al—Artificial lake, stock pond, or mining pond
Artificial lakes made by anthropogenic dams for use as stock ponds and/or ponds for mining operations. Most standing water is ephemeral.

Surficial Deposits

Ql—Ephemeral lake
Playas/ephemeral lakes filled with fine-grained sediment. In the northeast part of the quadrangle, two playa areas are formed on top of landslide blocks in sunken depressions at the head of the translated material.

Qa—Alluvium
Undifferentiated alluvial material filling major wash drainages and their tributaries; consists of sand, silt, clay, and gravel. Deep arroyo incision (up to 10–20 m/30–60 ft) is evident in some areas; the most notable areas in Sundance Wash along County Road 16 in the northeastern part of the map area and in Bread Springs Wash near NM-602 at the western boundary.

Qc—Colluvium
Deposits of hill-slope gravel, sand, and soil. At UTM 12S 0715304m E, 3925179m N in the northeast portion of the quadrangle, **Qc** appears to be graded to a higher relic surface (possibly **Qap**) that is now incised and eroded by active wash channels.

Qcf—Colluvium, fine-grained
Fine-grained, hill-slope material that flanks alluvium-filled washes. Differs from Quaternary colluvium by being sourced from fine-grained (mudstone- and shale-dominated facies) portions of Crevasse Canyon and Menefee Formations and is not always found at the base of slopes but at upper reaches of drainages. May reflect sheetflood deposition.

Qes—Eolian sand
Undifferentiated, unconsolidated, fine-grained, windblown sand; commonly reworks proximal sandstone outcrops. Some deposits display a reddish-orange color, which may be due to illitization. Up to 1 m tall coppice dunes are present at UTM 12S 0707427m E, 3926768m N. In the northeast part of the quadrangle on Jurassic Entrada outcrops, expansive biological soil crust is observed on **Qes**.

Qp—Younger piedmont-slope alluvium
Alluvial deposit in the northern part of the map area that forms a subtle fan northwest of the western ridge of The Hogback.

Qoa—Older alluvium

Undifferentiated alluvial material in broad-valley exposures that is not being incised by active arroyos. In the extreme northeast corner of the map area, may represent an alluvial (pre-Quaternary?) aggradational surface.

Qdic—Clinker in Dilco Member, Crevasse Canyon Formation

Brick-red colored deposit likely formed from the burning of aerially exposed coal. The age is uncertain but likely late Neogene to Quaternary given the landscape position.

Qap—Perched Valley-Fill Alluvium

Valley-filling alluvium, located in Mancos Shale strike valley, in the northeastern portion of the map area. Qap formed from landslides that impounded alluvial material and caused local depocenters above the younger and lower-elevation Qa surface. Sheetwash/fine-grained colluvial material eroded from flanking ridges of The Hogback appear to have collected toward an axial position that is not yet incised.

Qls—Landslide

Undifferentiated landslide deposits and slope-failure debris found in steeply dipping strike valleys in the northeastern portion of the map area. Largely characterized by translated bedrock and colluvial cover in strike valleys. Where discernible, deposits are broken out by their sourced units:

> Qlst—Landslide deposits and slope-failure debris sourced from Late Cretaceous Torrivio Sandstone member of the Crevasse Canyon Formation; failure occurred in uppermost Torrivio or lowest Dilco Member and slid down dip into the strike valley.
>
> Qlsg—Landslide deposits and slope-failure debris sourced from Late Cretaceous Gallup Sandstone; failure occurred in Mancos Shale and slid against dip of bedding into the strike valley. Appear to be a type of topple (block or flexural) or slide (planar or wedge), as Gallup Sandstone bedding within the translated block is subhorizontal while in situ Gallup Sandstone in The Hogback has a 30–40° dip to the west, suggesting a forward tilt rather than a backward tilt that would be expected for a rotational slump. Topple/slide here may have been due to an ancestral strike drainage that undercut Mancos Shale underlying the Gallup Sandstone prior to aggradation of current alluvial material filling arroyos. Deposits are poorly sorted in places, but appear as largely coherent blocks with bedding preserved in other locations.

Qlsd—Landslide deposits and slope-failure debris sourced from Late Cretaceous Twowells Tongue of the Dakota Sandstone; failure occurred in Mancos Shale and/or Whitewater Arroyo Tongue of the Mancos Shale and slid down-dip into strike valley. Deposits appear blocky and catastrophic given a poorly sorted nature.

Quaternary–Tertiary (age uncertain)

QTpg—Perched Gravel Deposits

Unconsolidated pebble- to boulder-sized gravel deposits south of the modern Bread Springs Wash. Deposits become coarser-grained from west to east toward the Zuni Mountains. Clasts also vary from west to east: western deposits (UTM 12S 714155m E, 3919956m N) are more varied and consist mostly of Permian Glorieta sandstone derived from the Zuni Mountains and possibly Late Cretaceous Dakota and/or Gallup sandstones from the Zuni Mountains frontal fold (Nutria fold), as well as minor amounts of cherty material and white-purple rhyolite. Eastern deposits up to the eastern border of the map (UTM 12S 715638m E, 3919714m N) consist mostly of cobble- to boulder-sized (up to 0.5 m across) clasts mostly of Permian Glorieta Sandstone with minor white-purple rhyolite. Elevation of the strath (base) of the deposits increases eastward toward the Zuni Mountains from 2,230–2,300 m elevation. Permian Glorieta clasts are likely sourced from a Laramide thrust sheet, the Stinking Springs thrust sheet, in the Zuni Mountains as mapped on the Anderson et al. (1998) Fort Wingate quadrangle. The white-purple rhyolite is of unknown source and age, but is hypothesized to be from the Mogollon-Datil Volcanic Field approximately 100 km to the south and southeast. It is uncertain if these deposits are linked to the Tertiary Bidahochi Formation west of here, or if they represent ancestral Bread Springs Wash deposits. However, the rhyolites may suggest a more regional drainage system.

Tertiary

Tb—Bidahochi Formation

Red-orange and cream-pink, fine-grained unit with interbedded thin-bedded sandstones. Sandstone is vfU to fL with ≤5–10% vCL to vCU quartz grains. Grains are moderately to well-sorted and subrounded to rounded; calcite cemented sandstone composed of 80–90% quartz, 10–15% lithics, 5–10% K-feldspar (pink and angular to subangular). A thin, white, friable chalky layer is also apparent near the base. Thin-bedded sandstone 10–12 cm thick and 1 m above the base appears to be laterally continuous in this area. Fine-grained layers appear to be composed of unlithified and/or reworked very fine sand that is well-sorted and rounded, composed of 95% quartz, 4% lithics, and 1% K-feldspar. Commonly reworked by eolian processes, forming an unconsolidated veneer on top of underlying sedimentary bedrock (Kmfg in the Bread Springs quadrangle). Tb differs from reworked unconsolidated sediment in Kmfg by exhibiting a red-orange color with polygonal desiccation cracks that are fist-sized (approximately 4-6 cm across); whereas, Kmfg unconsolidated sediment is typically red-brown, and polygonal desiccation cracks are 2-6 cm across and much less common.

MESOZOIC

Late Cretaceous

Terrestrial Units

Kmf—Menefee Formation

Variable sequence in the southeast part of the map composed of pinkish-white to light-tan sandstone that is inset and/or cut into olive-drab Cretaceous shales; contains purple-gray shales, rust-brown concretionary sandstones, and locally weathers to red-white. Stacked channel complexes with pervasive trough cross-beds are noted in a roadcut along Bread Springs Road; some sandstone bodies exhibit leaf fossils. Unit is ambiguously listed as Cretaceous or Tertiary given characteristics of facies that are similar and dissimilar to both Kmfg and Tb, and it is currently unclear if this unit represents a Cretaceous inset channel deposit or the upstream source-proximal channel of the Bidahochi Formation.

Kmfa—Allison Member

Variable interbedded sequence of predominantly yellowish-gray and dusky-yellow to olive-drab weathered shale and pale-orange to whitish-yellow, very fine- to medium-grained, moderately well to poorly sorted sandstone. Cross-bedding is pervasive; coal is uncommon to absent. Located only in the northwest corner of the Bread Springs quadrangle.

Menefee and Crevasse Canyon Formations

Kmfg—Gibson Coal Member of Crevasse Canyon Formation and Cleary Coal Member of Menefee Formation, undivided

Variable interbedded sequence of sandstone, siltstone, shale, and coal. Lower part is dominantly fine-grained, olive-drab and characteristic silver-blue weathered shales with whitish-yellow to orange, cross-bedded sandstones. Upper part consists of apparently tabular thick-bedded cross-bedded sandstone packages (at least three beds) with interbedded shales and coal. Coals are commonly discontinuous and up to 40 cm thick (occasionally thicker). **Kmfg** is distinct from **Kcdi** by exhibiting rust-brown concretionary sandstones and silver-blue weathered shales (common along NM-602, south of Gallup). Fossil woody debris that displays a glossy rust-brown appearance is common and occasional petrified wood and logs are observed. Large channel bodies are apparent in places cutting into lower facies. At UTM 12S 0715582m E, 3919784m N, a gray- and brown-weathered carbonate with minor lithic clasts was observed. Carbonate weathered to dark-brown, gray on fresh surface, and exhibited a rough and sharp surface. **Kmfg** is approximately 90 m (300 ft) thick.

Crevasse Canyon Formation

Kcb—Bartlett Member

As mapped, the Bartlett member consists of a thick- to massive-bedded, whitish-yellow sandstone that erodes into a bulbous nature. This sandstone is in sharp contact with underlying **Kcdi**; overlying **Kmfg** forms an approximate contact. In most places, **Kcb** is mapped solely as the sandstone, but at UTM 12S 709738m E, 3922802m N **Kcb** is interpreted based on no apparent coal seams and only coalified tree fossils. In the Bread Springs quadrangle, **Kcb** is characterized by a grayish-white silty to sandy facies devoid of coal seams. Possibly as much as 45 m (150 ft) thick overall, but thinner where mapped as a single sandstone package.

Kcdi—Dilco Member

Variable interbedded sequence of shale and carbonaceous shale, coal, siltstone, and sandstone. Distinct olive-drab weathered shales are very common with medium- to thick-bedded, pale-orange-yellow to white sandstone; some sandstones are tabular while others are distinctively channel bodies that occasionally are observed to cut into underlying facies. Coal seams are common, and range from approximately 16 cm thick but can be up to meter-scale thickness; white petrified wood can be found in some coal seams. Thin- to medium-bedded, friable, white-gray sandstones are also common. A medium-bedded (1–2 m thick) sandstone bed that weathers to white (**Kcdikb**) is located in the upper portion of **Kcdi** and can be correlated across the map area; this bed separates the lower **Kcdi** facies from an upper **Kcdi** facies approximately 30 m (100 ft) below upper contact with **Kcb**. **Kcdi** and **Kmfg** facies can appear similar, but Kcdi does not exhibit silver-blue shales or rust-brown concretionary sandstones. At UTM 12S 0706714m E, 3929574m N, a thin (10 cm thick) limestone bed was observed with pervasive cone-in-cone structures. Unit is approximately 140 m (460 ft) total thickness.

Kcdikb—Key bed of the Dilco Member (map only)
A medium-bedded, whitish sandstone in the upper part of **Kcdi**, 1–2 m (3–6 ft) thick. This sandstone separates lower **Kcdi** facies from the upper, approximately 30 m (100 ft) of **Kcdi** that is below the **Kcb** contact. The sandstone body can be correlated across the map area and serves as a distinctive marker bed.

Kct—Torrivio Sandstone Member
Distinctive pinkish to white, medium- to coarse-grained, poorly to moderately sorted sandstone with subangular to subrounded grains; locally arkosic. Notably differs from underlying Gallup Sandstone lithology in color, presence of feldspar, and apparent total lack of bioturbation that may suggest a change from marine to non-marine conditions. Unit is approximately 20 m (65 ft) thick.

Marine and Marginal Marine Units

Kg—Gallup Sandstone
Pale-orange-yellow to white-yellow, very fine to fine-grained (vfU to fU), subrounded, moderately to well-sorted quartz-dominated sandstone with abundant trough cross-beds and bioturbation. Three sandstone bodies separated by shale, carbonaceous shale, and coal horizons are observed in the quadrangle, referred to by Molenaar (1973) in descending stratigraphic order as the D, E, and F sandstones. Upper contact (where observed) is mapped as a coal horizon that is in sharp contact with **Kct**. Unit is approximately 90 m (290 ft) thick.

Km—Mancos Shale
Dark-gray to black, fissile shale, weathers yellow to olive-drab; forms recessive hill slopes and strike valleys. Outcrops are rare but present on the backside of ridges beneath overlying Gallup Sandstone (F sandstone) in the northeast part of the quadrangle. Lower contact with **Kdt** is sharp and upper contact with **Kg** appears sharp. Possibly represents the Rio Salado Tongue of the Mancos Shale, according to Anderson (1991). Bridge Creek Limestone Member of Greenhorn Formation may be present in the lower half, but was not observed in the Bread Springs quadrangle due to colluvium and mass-wasting deposits that cover exposures. Unit is approximately 120 m (400 ft) thick.

Kdt—Twowells Tongue, Dakota Sandstone
White to gray, fine-grained (fL), moderately sorted, subrounded silica-cemented sandstone that weathers olive-gray to yellow. Where observed, the base of **Kdt** is a medium-bedded (20 cm thick), fine-grained (fL) sandstone that exhibits vertical burrows. The northernmost exposure in the map area exhibits a systematic subvertical

orthogonal joint pattern that could enhance fluid flow permeability in the subsurface to the west of the outcrop area.

Kmw—Whitewater Arroyo Tongue, Mancos Shale

Dark-gray to black, fissile shale, weathers yellow to olive-drab; forms recessive hill slopes and relatively narrow intermediate strike valleys between Kd and Kdt. Outcrops are rare. Lower and upper contacts with Kd and Kdt, respectively, are sharp.

Kd—Dakota Sandstone

Well-indurated, buff-white, fine- to medium-grained (fU to mL), well-sorted, rounded, silica and calcite cemented quartz arenite that weathers to olive-drab to yellow-white. Locally weathers to reddish in the northeastern part of the map area. Bioturbation, symmetric ripples, and cross-bedding (trough and planar) are present. In the quadrangle, the base of Kd on Jm is disconformable (possibly slight angular unconformity) and comprises an approximately 4 m (13 ft) thick package of fine to coarse sandstone and interbedded shale and coal; the base is followed by a 10 m (33 ft) thick black shale that weathers gray and is capped by a thick-bedded, cross-bedded, fine-grained sandstone. Basal scouring geometries expose different parts of the lowest Dakota Sandstone and in places contain thin coal beds and olive-gray shale below the main medium- to thick-bedded Dakota Sandstone body. The northernmost exposure in the map area exhibits a systematic subvertical joint pattern (locally orthogonal) that could enhance fluid flow permeability in the subsurface to the west of the outcrop area.

Kdmu—Undivided Dakota Sandstone, Mancos Whitewater Arroyo Tongue, and Dakota Twowells Tongue (Cross Section only)

Combined units for cross sections. Units are approximately 90 m (300 ft) thick.

Jurassic

Jm—Morrison Formation, undivided

Grayish-pink to pink-red, friable to indurated, medium- to coarse-grained sandstone and conglomeratic sandstone with trough cross-bedding. Below the base of **Kd**, consists of a white, poorly sorted cross-bedded conglomeratic sandstone that exhibits kaolinite rhombs and pebbles. The middle to lower part consists of yellow and gray muds, white-pink sandstone, and red sandstone. Unit is approximately 60 m (200 ft) thick.

Jz—Zuni Sandstone

"Candy-striped" red and white, thin- to medium-bedded, fine-grained (vfU), subrounded, moderate- to well-sorted eolian sandstone that forms resistant cliffs and slopes. Some white beds consist of resistant, interbedded carbonates that are lenticular. Striping is 15–50 cm thick. Planar and trough cross-beds are in small/thin approximately 10-cm-scale sets that differ in magnitude from large-scale cross-beds of underlying **Je**. Unit is approximately 75 m (250 ft) thick.

Jt—Todilto Formation

Thin-bedded, white to gray, sandy carbonate and evaporite deposit. Contains interbedded folding that has been interpreted to represent algal mounds/stromatolites (e.g.: Lucas et al., 2021). Unit is approximately 30 m (100 ft) thick.

Je—Entrada Sandstone

Distinctive red-orange, very fine- to fine-grained, massive-bedded eolian sandstone with large (10-m-scale) cross-beds. Sand grains are subrounded to rounded and well-sorted. Weathers to pale-orange with thin stripes/stringers of dark-pink, white, and gray. Up to 90 m (300 ft) thick on the Bread Springs quadrangle and as much as 180 m (600 ft) thick on the Fort Wingate quadrangle to the east.

Triassic

ꞦTo—Owl Rock Formation

Light- to dark-gray, very fine-grained to silty limestone bed that weathers to bluish-purple and orange-yellow in places. The top surface has a rough and jagged "rip pants" texture. Resistant to weathering and forms a small hogback ridge in the northeast corner of the map area. Unit is approximately 1–2 m (3–6 ft) thick.

Ꞧp—Petrified Forest Formation, undivided (cross section only)

Purple to red package of mudstone, sandstone, and siltstone. According to Anderson et al. (1998), the Petrified Forest Formation comprises the lowest Blue Mesa Member, Sonsela Sandstone Member, and upper Painted Desert Member. Only the upper Painted Desert Member is exposed on the Bread Springs quadrangle. Up to 230 m (750 ft) in total thickness.

> **Ꞧpp—Painted Desert Member, Petrified Forest Formation**
>
> Pale- to deep-purple, pale-reddish-brown, bluish-white, and light-greenish-gray mudstone, sandstone, and siltstone. Smectitic facies are common in mudstones. Forms low-relief landscape in the northeast corner of the map area. Total thickness, according to Anderson et al. (1998), is up to 165 m (550 ft) thick.

Ꞧb—Bluewater Creek Formation, undivided (cross section only)

According to Anderson et al. (1998) and as observed in the Fort Wingate and Upper Nutria quadrangles to the east and southeast, respectively: consists of pale-reddish-brown, pale-red, dark-reddish-brown mudstone and silty mudstone. Three members are present, as modified from Anderson et al. (1998): the Lower Member, a reddish mudstone; the middle McGaffey Member, a white to gray sandstone with basal carbonate clast conglomerate; and the Upper Member, again, a reddish mudstone unit. Unit thickness is up to 80 m (270 ft) thick.

Moenkopi Formation and Shinarump Formation, undivided ***(cross section only)***

Ꞧm— Moenkopi Formation and Shinarump Formation, undivided (cross section only)

As modified from Anderson et al. (1998) based on observations in the Upper Nutria quadrangle to the southeast: moderately reddish-orange to white-purple, medium- to thick-bedded sandstone that exhibits planar and trough cross-beds. Base consists of a mottled white, purple, and black, pebble-clast conglomerate. Above the Moenkopi is the Shinarump Formation which exhibits chert- and quartzite-pebble clast conglomerates and conglomeratic sandstone with yellow muds. Unit is as much as 20 m (70 ft) thick or more.

PALEOZOIC

Permian

Pu—Permian, undivided (shown on cross sections only)
Combined unit consisting in stratigraphic ascending order of the Abo, Yeso, Glorieta Sandstone, and San Andres formations. Abo Formation is a brick-red siltstone to sandstone with cross-beds and white reduction spots; Yeso Formation is an orange to orange-red sandstone to mudstone that locally exhibits three carbonate beds in the upper parts of the unit; Glorieta Sandstone is a characteristic orange to orange-white, fine-grained eolian sandstone that is pervasively cross-bedded; the San Andres Formation is a limestone that is locally karsted and absent. Unit thickness is as much as 330 m (1,000 ft) total thickness. Unit descriptions are based on observations from the Upper Nutria quadrangle that is southeast of the map area.

PRECAMBRIAN

Proterozoic

p€u—Basement, undifferentiated (shown on cross sections only)
Early Proterozoic medium-grained, equigranular, biotite granite, according to Anderson et al. (1998).

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