Geologic map of the Llaves 15-minute quadrangle, Rio Arriba County, New Mexico

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INTRODUCTION

The Llaves 15-minute quadrangle is located about 25 miles (40 km) north of Cuba, NM on the eastern flank of the San Juan Basin. Geologic structures in this area primarily formed during compressional Laramide deformation. The south end of the Gallina-Archuleta anticlinorium, a northward extension of the Sierra Nacimiento Laramide highland, crosses the eastern half of the quadrangle. The Gallina-Archuleta anticlinorium separates the San Juan Basin to the west from the Chama basin to the east. Syn-orogenic sedimentary rocks deposited in the San Juan Basin during Laramide deformation are exposed in the western half of the quadrangle. The eastern margin of the San Juan Basin is marked by a prominent, curving, west-dipping monocline to the west of the faulted Gallina uplift. The sedimentary bedrock in the area ranges in age from Pennsylvanian to Eocene; these rocks contain a rich, but fragmentary, geologic record spanning approximately 275 Myr. Remnants of ancient river systems, vast deserts, saline lakes, broad mudflats, and oceanic shorelines are preserved in this area.

The Continental Divide crosses through the western part of the quadrangle (Fig. 1). The main drainage in the area, the Rio Gallina, is a tributary to the Rio Chama. This river is semi-perennial; portions of the Rio Gallina are fed by perennial springs in the narrow canyon north of French Mesa (**Figure 1**).

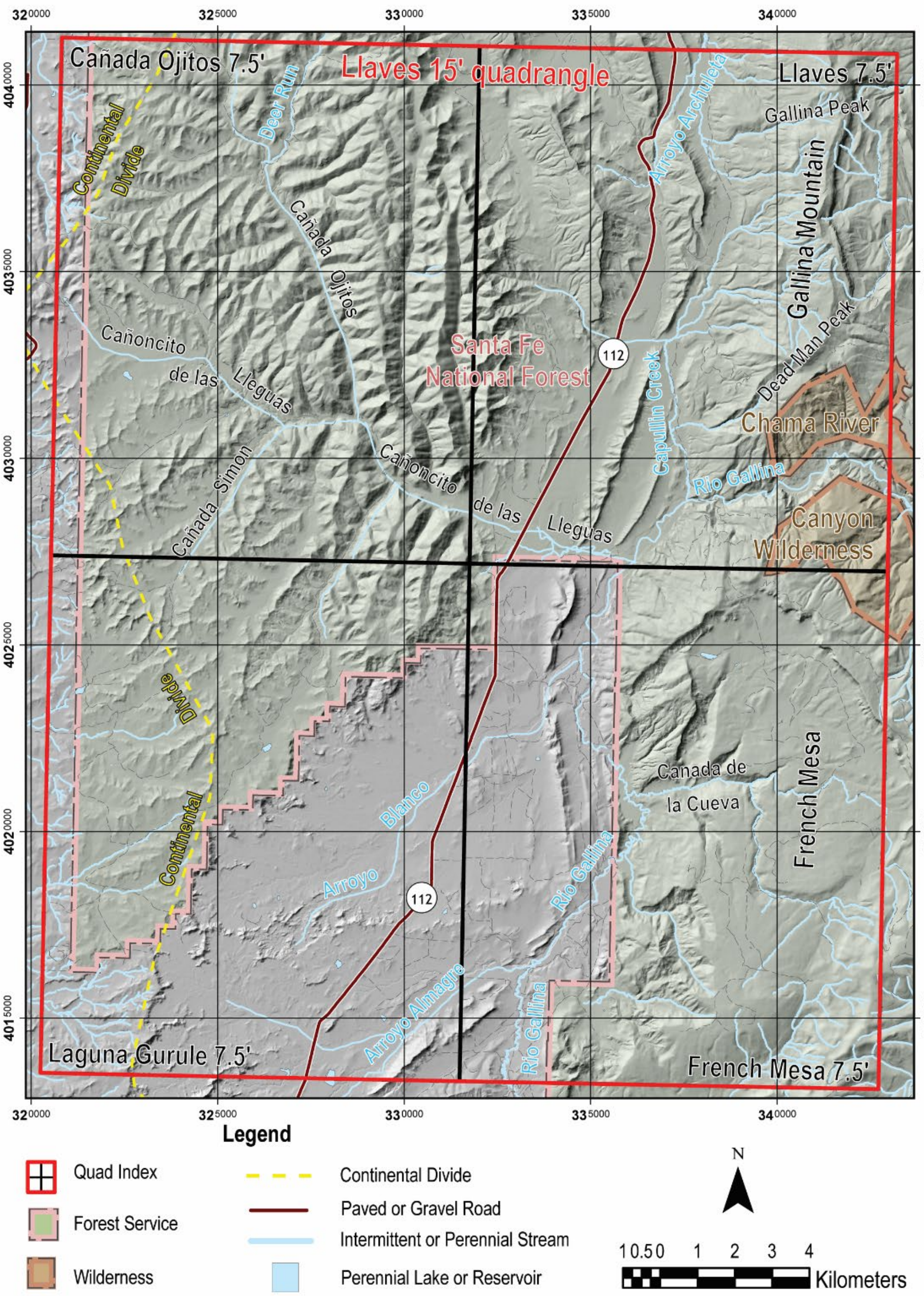

Figure 1—Geographic location map of Llaves 15-minute quadrangle.

PREVIOUS WORK

The mapped area is included on the regional-scale geologic maps of Baltz (1967), Bingler (1968), and Manley et al. (1987). Baltz (1967) described the stratigraphy and geologic structures in this area. Fassett and Hinds (1971) did a reconnaissance study of the Cretaceous stratigraphy. Several University of New Mexico graduate students produced Master's theses describing the geologic structure of the Gallina uplift, which is on the south end of the Gallina-Archuleta anticlinorium (Lookingbill, 1953; Fitter, 1958; Crouse, 1985; and Hultgren, 1986). A geologic map of the French Mesa 7.5′ quadrangle (Crouse et al. 1992) and a paper by Woodward et al. (1992) summarize the structural features on the Gallina uplift. Ridgley (1983) incorporated the Rio Gallina anticline into her map of the Chama River Canyon Wilderness. Smith (1988, 1992a, b) described the stratigraphy and sedimentation of the uppermost Cretaceous and Paleogene sedimentary rocks along the eastern margin of the San Juan Basin.

GEOLOGIC HISTORY

Detailed descriptions of the rock units exposed in the Llaves 15-minute quadrangle are presented at the end of the report.

Pennsylvanian

The oldest rocks exposed in the Llaves area, located in the northeastern corner of the map area, are interbedded green and red arkosic sandstone, and a sandy fossiliferous limestone that are about 320 to 300 million years old. These sedimentary rocks were deposited along the shore of a shallow ocean that once covered the southern two-thirds of the state of New Mexico during late Pennsylvanian time. Wood and Northrup (1946) called these rocks the "arkosic limestone member of the Madera Limestone." The arkosic material was likely derived from the Ancestral Rocky Mountain Peñasco highland (Woodward, 1987) located just south of the quadrangle, which occupied the current location of the Sierra Nacimiento.

Latest Pennsylvanian to Permian

Starting about 300 Ma, the shoreline retreated toward the south, and a south-flowing river system drained the region. The Cutler Formation contains cobbles and pebbles of Proterozoic quartzite and granite likely derived from the Ancestral Rocky Mountain Uncompahgre uplift to the northeast. As time progresses, siltstone becomes more common and channel sandstone is much less common upsection in the Cutler Formation, indicative of a drying climate.

Triassic

Approximately 47 million years of Earth's history are missing at the contact between the Cutler Formation and the Chinle Group. The Late Triassic Chinle Group, a thick package of brick-red to red siltstone and mudstone and white to tan sandstone, consists of rocks that were deposited by rivers between 205 and 225 Ma, when the Llaves area was located about 10° north of the equator. The basal Agua Zarca Sandstone is a white to yellow to green, coarse-grained quartz sandstone that locally contains abundant quartzite cobbles; this sandstone is overlain the maroon shales of the Salitral Formation. The Agua Zarca and Salitral Formations are exposed in the Gallina Mountain anticline, but are absent in the Rio Gallina anticline due to nondeposition or erosion. Fitter (1958) notes that these two formations are thin on French Mesa. A second conglomeratic sandstone–mudstone sequence sits on top of the Agua Zarca/Salitral package. This sequence is composed of the Poleo Formation, a medium-bedded, yellowish-gray micaceous sandstone with conglomeratic lenses of siltstone and calcrete clasts; a thick red to reddish brown mudstone, the Painted Desert Member of the Petrified Forest Formation, overlies the Poleo Formation. In many places, a transitional, thinly bedded sandstone, the Mesa Montosa Member of the Petrified Forest Formation, is present between the Poleo Formation and the Painted Desert Member. The Poleo Formation and Mesa Montosa Member sandstones are exposed in the Rio Gallina and the Gallina Mountain anticlines. The Chinle Group was deposited by Mississippi River-scale river systems flowing from central Texas toward the northwest, to Nevada. The youngest Chinle Group unit, the Rock Point Formation of Lucas et al. (2005b), is not exposed in this area.

Jurassic

Another significant gap in the rock record (unconformity), spanning about 44 Myr, occurs between the late Triassic rocks and the middle Jurassic rocks. The oldest of the middle Jurassic rocks, the Entrada Sandstone, forms the prominent red, yellow, and white cliffs in the cores of the three anticlines in this area. The Entrada Sandstone contains spectacular cross-beds that are several meters high, indicating an eolian (windblown) origin for this unit. The Entrada Sandstone deposits in the Llaves area are part of a vast dune field that covered much of northern New Mexico, southwestern Colorado, southeastern Utah, and northeastern Arizona (Korurek and Dott, 1983; Blakey, 1994; Peterson, 1994). Paleocurrent indicators show that the Entrada sands were transported by wind blowing toward the south to southwest (Tanner, 1965). The Entrada Sandstone is estimated to be approximately 166 to 164 million years old. The Todilto Formation, which consists of a basal limestone and shale unit (the Luciano Mesa Member) and, in places, up to 30 m of gypsum (the Tonque Arroyo Member), was deposited on the Entrada Sandstone. The contact between the Entrada Sandstone and the Luciano Mesa Member of the Todilto Formation is relatively flat and quite sharp, which has led Ahmed Benan and Kocurek (2000) to speculate that the Entrada dune field was flooded catastrophically, with very little reworking of the sand dunes. The Todilto Formation was most likely deposited in a salina (Lucas et al., 1985); in other words, in a moderately deep, oxygen-poor, body of saline water that was isolated by a barrier from the main body of the Jurassic ocean located to the northwest, in east-central Utah (the Sundance Sea). Limestone of the Mesa Luciana Member precipitated from the evaporating saline water. Anderson and Kirkland (1960) noted that the basal limestone was deposited in thin layers, with each layer consisting of limestone, clay, and dark organic material. Each layer, or varve, represents a one-year cycle related to seasonal variations in runoff, water temperature, and abundance of lake organisms. Anderson and Kirkland (1960) carefully counted the varves and found that it took 14,000 years for the basal laminated limestone to accumulate. Later, as the saline waters of the salina became more concentrated by evaporation, gypsum precipitated. The Todilto Formation, based on fossil evidence (Lucas et al., 1985), is approximately 159 million years old. The Todilto Formation grades up into the Summerville Formation.

The basal 8–12 m of the Summerville Formation is a pale-red to white, ripple-marked sandstone. The basal sandstone unit is overlain by maroon mudstone and pinkish-tan, poorly cemented sandstone and minor limestone deposited on an arid coastal plain (Lucas et al., 2005a). Pedogenic carbonate is common in the maroon mudstone, particularly near the top of the unit. The Bluff Sandstone, which is exposed near the top of the Summerville Formation, represents a return to eolian deposition in this area. Cross-beds in the Bluff Sandstone record winds blowing toward the east, suggesting that the Llaves area on the North American continent had drifted north into the zone of prevailing westerlies (Lucas and Anderson, 1998).

An unconformity between the Summerville Formation and the overlying 155 to 148 Ma Morrison Formation marks a time of major plate tectonic reorganization of the southwestern United States and a shift from an arid to a more humid environment in this region (Lucas and Anderson, 1998). The Westwater Canyon Member is a white, trough-cross-bedded, channel sandstone that is discontinuously preserved across the Llaves quadrangle. The Brushy Basin Member of the Morrison Formation is made of pistachio-green and red mudstone with a few interbedded tan-sandstone beds. The Morrison Formation was deposited by rivers flowing toward the northeast across a broad muddy floodplain that dipped toward the north to northeast away from the developing Mogollon highlands in southwestern New Mexico and southeastern Arizona. Radiometric dating of ash beds ($^{40}Ar/^{39}Ar$ on sanidine; Kowallis et al., 1998) in the Brushy Basin Member in Utah and Colorado yields ages of 148 to 150 Ma for this unit.

Cretaceous

The west-dipping hogbacks that lie to the west of the three anticlines mentioned above are composed of Cretaceous coastal plain, shoreline, and marine units that were deposited along the western margin of the Western Interior Seaway 125 to 85 Ma. Approximately 25 Myr is missing across the contact between the Late Jurassic Morrison Formation and the Early Cretaceous Burro Canyon Formation. The Burro Canyon Formation consists of cross-bedded, medium- to fine-grained sandstone, quartz and chert pebble conglomerate, and pale-green to pale-red mudstones (Ridgley, 1977; Ridgley 1987; Owen et al., 2005). The unit was deposited by braided streams flowing towards the northeast to north, toward the Western Interior Seaway. This unit is about 100 to 125 million years old (Owen et al., 2005; Varney, 2005). The overlying Dakota Sandstone is composed of interbedded tan- to yellow-brown-weathering sandstone and dark-gray carbonaceous shale and siltstone. Ripple marks on tops of sandstone beds are common. The sandstones are locally cross-bedded, but, in general, the sandstones were intensely burrowed by marine organisms living in the shallow water along the shores of the Western Interior Seaway. The Dakota Sandstone records the alternating rise (shale) and fall (sandstones) of sea level as the shoreline moved back and forth across the area approximately 97 to 100 Ma.

A major marine transgression (relative rise of sea-level) is recorded by the Mancos Shale, which was deposited in deeper portions of the Western Interior Seaway 95 to 80 Ma. Seven members of this unit are recognized in this area (see unit descriptions). Limestones in this sequence represent the highest sea-levels, whereas shale indicates some distance from shore. The rare sandstones in the Mancos represent relatively near-shore environments. Deposition of the Point Lookout Sandstone between 85 and 84 Ma indicates a retreat of the sea to the northeast. Deposition of the coal and deltaic (are they all delta sandstones?) sandstones of the Menefee Formation between 84 to 80.5 Ma indicate continental (dry land) deposition. Sea level then rose again and deposited the nearshore Cliff House Sandstone (80.5 to 79.5 Ma) and deeper-water Lewis Shale (79.5 to 76.5 Ma). The Western Interior Seaway retreated for good with the deposition of the nearshore Pictured Cliffs Sandstone (which is thin or absent on much of the Llaves quadrangle) between 76.5 and 75.5 Ma. The deltaic Fruitland Formation coal and sandstones (75.5 to 74.5 Ma; the associated Kirtland Shale is absent in this area.) represent another return to continental deposition.

Paleogene

The tan, cliff-forming, fluvial sandstones of the Ojo Alamo Sandstone were deposited about 65 Ma in a south- to southeast-flowing river system. The Ojo Alamo Sandstone grades upward into the Nacimiento Formation. The basal Nacimiento Formation is dominated by mudstones and the upper part is composed of thick fluvial-channel sandstone. This unit was deposited by a northeasterly to easterly flowing trunk stream located several kilometers to the north of the Llaves quadrangle; the 65 to 58 Ma deposits left by northerly flowing tributaries draining into this trunk stream are preserved on the Llaves quadrangle (Cather et al., 2019).

Eocene

Remnants of two river systems are preserved in the 55 to 50 Ma San Jose Formation (Smith, 1988). The older system, represented by the channel sandstones of Cuba Mesa Member and the floodplain deposits of the Regina Member, flowed to the south, parallel to Laramide mountain fronts to the east of the river. The younger stacked-channel sandstones of the Llaves Member and the floodplain deposits of the Tapicitos Member were derived from source areas in the Brazos Cliffs area, to the east. Paleocurrents indicate that these rivers flowed to the west-southwest.

Quaternary

Mass wasting, fluvial, alluvial, lacustrine, colluvial, eolian, slope wash, and anthropogenic processes were all active in the Llaves quadrangle during the Quaternary as this area transitioned from one of deposition and preservation of sediment to one of overall erosion and landscape incision. Mass wasting includes large slump blocks as well as minor translational slides, rock falls, and lateral expansion. Fluvial terraces featuring locally derived and exotic cobbles are found up to 100 m above grade throughout the map area, in proximity to Rio Gallina and its tributaries. Multiple generations of alluvial terraces are found on the banks of the modern drainages. Multiple internally drained lacustrine deposits are found in the far reaches of alluvial drainages and on top of mesas. Thick colluvial aprons can be found on the slopes of Gallina Mountain while minor talus aprons and piles of undifferentiated debris are found elsewhere. Eolian deposition is widespread but insignificant until in close proximity to the active alluvial drainages that provide a source for windblown sediments. Slope wash along with alluvial and eolian deposition left deposits throughout the map area. Anthropogenic influence is widespread and includes roads, dwellings, stock tanks, and oil & gas infrastructure.

Local travertine (paleospring) deposits are preserved on brecciated Tonque Arroyo Member of the Todilto Formation in the vicinity of 13S 339932m E, 4029887m N NAD83. Dissolution of the gypsum in the Tonque Arroyo Member has left behind a limestone-chip breccia in this area that appears to have served as a conduit for local spring activity.

GEOLOGIC STRUCTURES

The main faults in this area are the north-northeast striking Gallina and Tierra Montañosa normal faults, which are at the north end of the greater Pajarito-Nacimiento reverse fault system that bounds the west side of the Sierra Nacimiento to the south (Woodward et al. 1992). Three structural domes (or doubly plunging anticlines) form the Gallina uplift.

The southernmost doubly plunging anticline is located on French Mesa, which is bound on the west side by the west-down Gallina fault. In one place, Permian Cutler Formation is juxtaposed against the Jurassic Entrada and Todilto formations. The Nacimiento fault (the reverse fault bounding the west side of the Sierra Nacimiento) is also west-down, but the Nacimiento fault vanishes south of French Mesa. The Gallina fault vanishes at the north end of French Mesa, south of the Rio Gallina and offset is transferred to the north along the east-down Tierra Montañosa fault.

The middle anticline is located to the north of the Rio Gallina **(Figure 2)**. The Rio Gallina anticline is bisected by the Tierra Montañosa fault, which juxtaposes Permian Cutler Formation on the west against Triassic Chinle Group to the east. The fault is well exposed in places **(Figure 3)** and springs are common along the Tierra Montañosa fault north of the Rio Gallina. The fault is high-angle and both the Cutler Formation and the Poleo Sandstone on the west side of the fault dip steeply to the east adjacent to the normal fault.

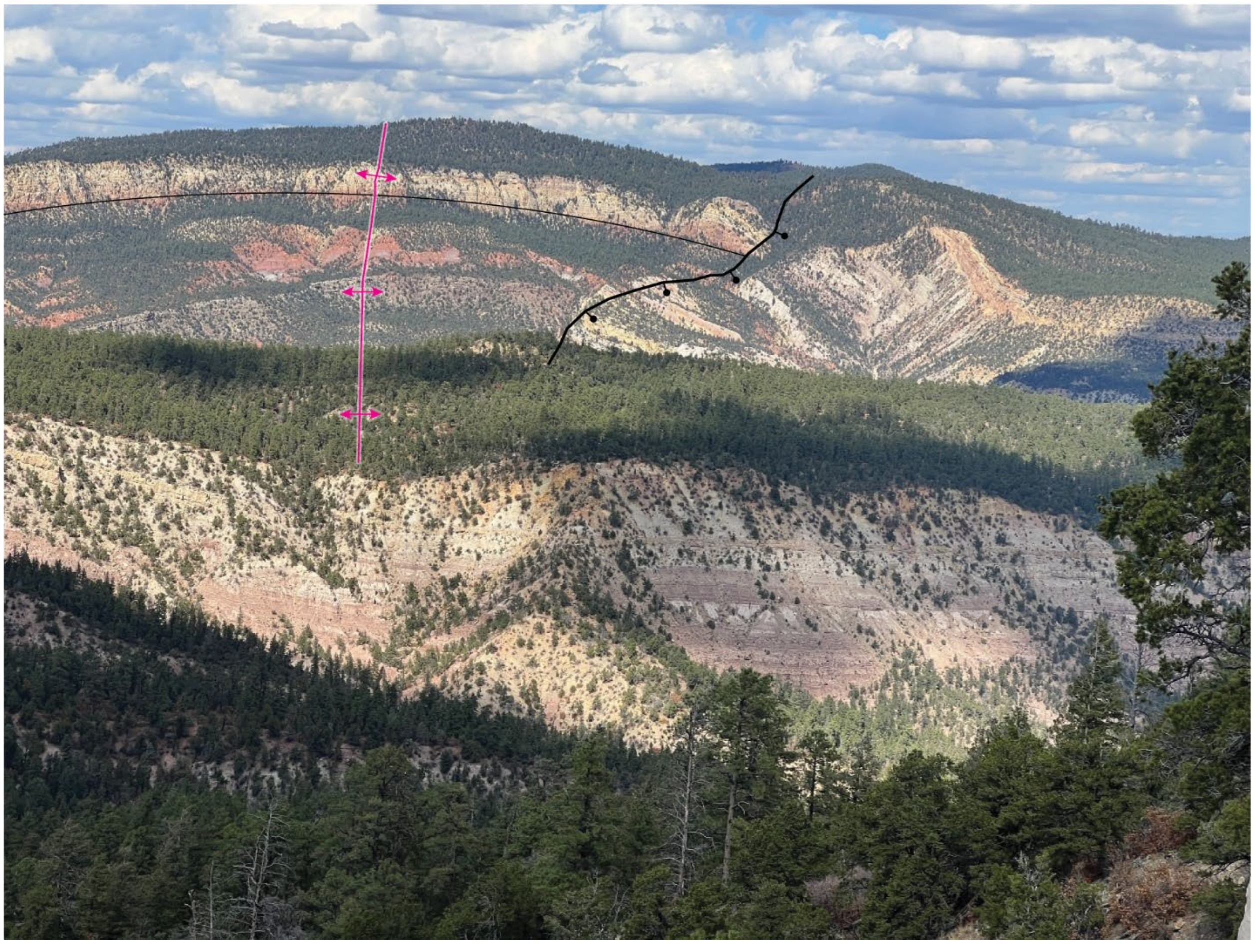

Figure 2—Rio Gallina anticline in distance with major offset observable from the Tierra Montañosa fault.

The northernmost anticline, located to the east of Gallina Mountain, is elongated N-S with the axis of the fold to the west of the Tierra Montañosa fault. Folded Pennsylvanian sandstones and a limestone bed on the west side of the fault are juxtaposed against Cutler Formation to the east.

Woodward et al. (1992) argue that the Gallina fault has both dip-slip and strike-slip components and that the Tierra Montañosa fault is primarily dip slip. The Tierra Montañosa fault is well exposed in the Rio Gallina anticline at 13S 340913m E, 4030327m N NAD83. In this outcrop, north-striking fault planes dip 55° W to 85° E with dip-slip to slightly oblique-slip (rake 75° S) slickenlines. A second set north-striking fault planes dip 85 W with dip-slip slickenlines that cut older low-angle slickenlines, indicating a change in slip direction along this fault (**Figure 4**).

Figure 3—The Tierra Montañosa fault separates the red Petrified Forest Formation of the Triassic Chinle Group on the right from the orange-red Permian Cutler Formation to the left in the foreground. On the skyline, the fault separates the Poleo Formation on the right from Entrada Sandstone on the left.

Figure 4—North-striking (10°), west-dipping (85°) slickenlines cutting older low-angle slickenlines along the Tierra Montañosa fault. Finger on the low-angle slickenlines points toward the north.

Investigations of the Paleocene to Eocene syn-orogenic Ojo Alamo, Nacimiento, and San Jose formations by Baltz (1967) and Smith (1988, 1992a,b) have been used to document the timing and progressive development of Laramide uplifts and basins in this area. Smith (1988) examined the structural and stratigraphic relations of the Nacimiento and the San Jose Formations west of the Sierra Nacimiento and Gallina uplifts. He found that the basal Cuba Mesa Member of the San Jose Formation was deposited at a time of little tectonic activity and that the stacking of channels in the Regina Member indicate accelerated subsidence in the San Juan Basin. The Proterozoic core of the Sierra Nacimiento was not exposed during the deposition of the San Jose Formation; the Mesozoic and Paleozoic section was eroding from the highlands and providing sediment during the early phases of Laramide uplift. The Gallina-Archuleta arch apparently did not form until after Llaves Member deposition.

Baltz (1967) drew structural contours on the base of the Ojo Alamo Sandstone using the distinctive signature of this unit on geophysical logs from petroleum wells. The contours highlight a series of northwest-plunging folds that suggest right-lateral slip on the Nacimiento-Gallina fault system.

A sharp bend in the Cretaceous hogback belt separates northeast-striking beds in the monocline to the south from more northerly striking beds to the north. This bend is associated with a northwest-striking faulted syncline (Baltz, 1967; Crouse et al., 1985). South of the bend, the Schmitz anticline-syncline pair that appears to accommodate some of the strain associated with the bend lies just west of the hogback. These folds deformed the Regina Member of the San Jose formation.

Most San Jose Formation beds dip moderately to the west on the Llaves quadrangle. However, in one area between Canada Simon and Oso Canyon, in the west-central part of the map, Tapicitos Member beds dip variably and in places define north-northwest- to northeast-trending, low-amplitude folds. This area of deformation is found roughly on line with the above-mentioned bend in the outcrop belt. This alignment may or may not be coincidental.

QUATERNARY TERRACE GRAVELS

To better understand the geomorphic history of the map area—especially the Rio Gallina and its tributaries—clast counts were conducted in thirteen locations. Eleven counts were done on high gravel-terrace deposits (**Qg**), one count was done on an anomalously high lag deposit, and one on a gravel lens in the Llaves Member of the San Jose Formation (**PEsl**). In each deposit, counts were conducted within multiple randomly selected 1 m² areas for all clasts larger than fine gravel (>19 mm) until reaching a sample size of approximately n=200. Terrace gravels (**Qg**) of this publication were mapped as 'Colluvium' (Qc) and 'Terrace and Pediment Deposits' (QTtp) by Crouse et al. (1992), and as 'Terrace gravel, colluvium, and stream-channel gravel' (Qcg) by Baltz (1967), and in locations where no Quaternary gravel deposits had previously been mapped. Height above grade was measured perpendicular from the nearest continually channelized ephemeral or perennial drainage; this excludes small ephemeral creeks that transfer between channelized and non-channelized flow.

Clasts were divided into the following categories: quartzite, metaconglomerate, sandstone, limestone, petrified wood, claystone/siltstone, vein quartz, chert/chalcedony, mafic igneous, felsic igneous, volcanic, and other metamorphic. Deposits north of the stream draining the Cañoncito de las Leguas and north of Rio Gallina, downstream of its confluence with Cañoncito de las Leguas **(Figure 1)**, contain clasts that appear to be locally derived only. Meanwhile, south of those drainages, there are exotically derived clasts **(Figure 5)** including mafic, felsic, and volcanic igneous clasts as well as limestone and metamorphic lithologies besides quartzite and metaconglomerate. Distance above grade did not seem to have significant effects on the clasts counts either north or south of the drainages. Sample number 4 has a greater quartzite value than other deposits south of Rio Gallina; however, this deposit likely hosts a greater input from locally derived materials compared to other southern deposits due to its proximity to the confluence of the two sources at 13S 337690m E, 4028847m N NAD83. These differences are detailed in **Figure 6** with plots of relative modal abundance based on geographic position (x-axis) and approximate height above grade (y-axis) while location, stratigraphic, sample size, and height above grade are given in **Table 1**.

Figure 5—Example clasts from a deposit south of Rio Gallina and its tributaries. This location (Sample 4) was still dominated by quartzite but had some exotic cobbles as well.

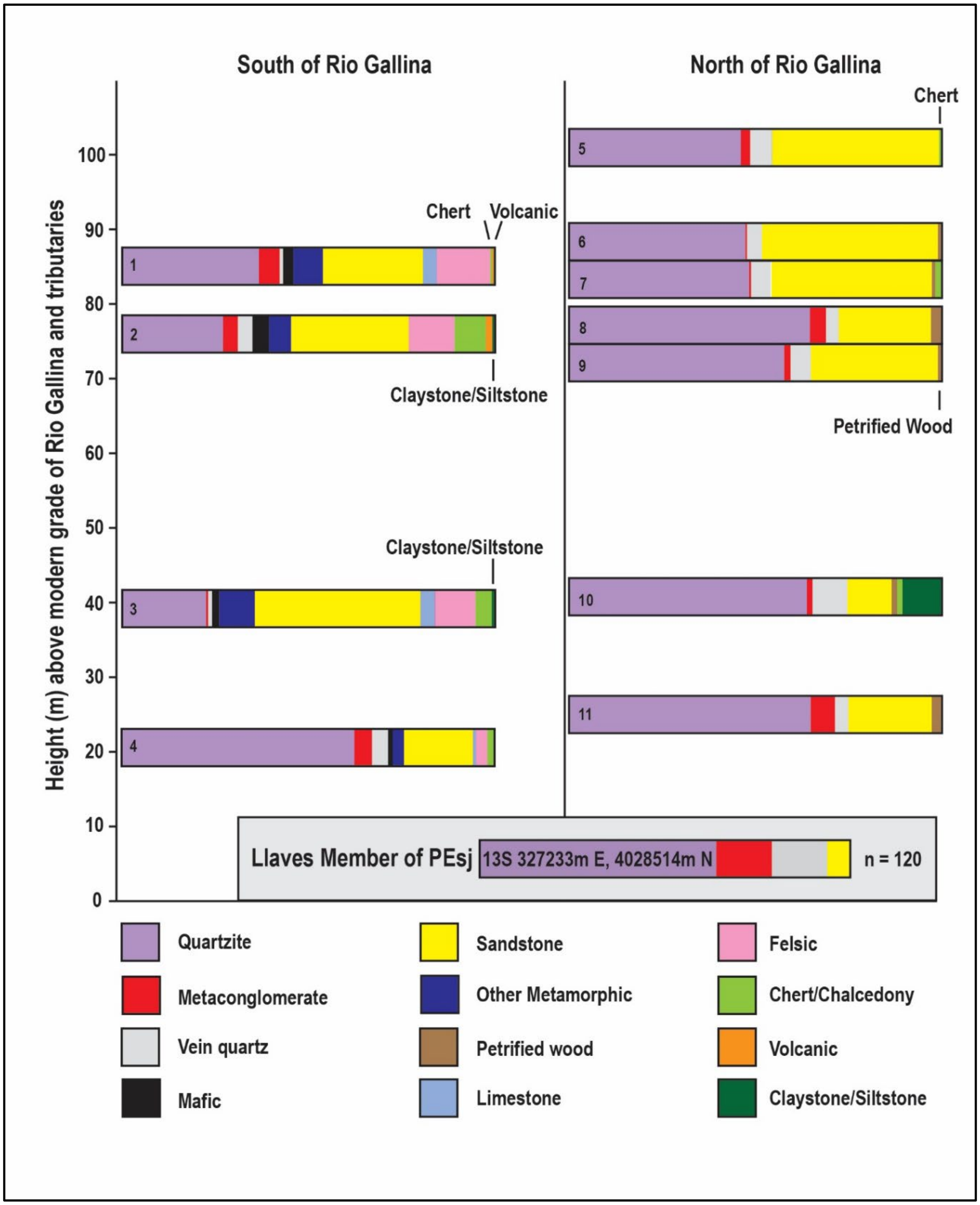

Figure 6—Relative modal abundance of rock-type categories found in terrace gravel deposits **(Qg)** at grades of 22 m to 98 m above the modern grade of Rio Gallina and its tributaries.

Sample	n=	Height Above Grade (m)	Overlying	UTM Coordinates (NAD 1983)
1	215	86	Kbc, Jm	13S 335870m E, 4018679m N
2	203	77	Kmcl/Kmjl	13S 332327m E, 4013378m N
3	200	38	Kmu	13S 333612m E, 4015885m N
4	232	22	Kmg	13S 337508m E, 4028567m N
5	200	98	PEoa	13S 334045m E, 4030817m N
6	247	87	PEn	13S 333346m E, 4030660m N
7	210	84	PEn	13S 333224m E, 4029873m N
8	258	77	Kd	13S 337967m E, 4029461m N
9	237	72	Kl	13S 335018m E, 4030806m N
10	203	40	Kpl	13S 334701m E, 4027706m N
11	245	24	QNcu, Kmg	13S 337681m E, 4029603m N

Table 1—Clast-count sample sizes, height above grade (m), coordinates, and formations over which they were deposited. Sample numbers correspond to labels in **Figure 6**.

Quartzite was typically very well-rounded and thought to be sourced as recycled clasts from the Eocene San Jose Formation from either the Cuba Mesa Member (**PEsc**) or the Llaves Member (**PEsl**). The nearest, and most probable, direct source would be from the Tusas Mountains approximately 205 km east-northeast; however, it is not believed to be directly sourced. Evidence for recycling of quartzite cobbles from the San Jose Formation includes sandstone matrix found on gravels within lag deposits **(Figure 7)** and the similarity between clast counts of the deposits with the Llaves Member of the San Jose Formation **(Figure 6)**. Metaconglomerate, which is inferred to have been originally in stratigraphic sequence with the quartzite, is also assumed to be recycled from the San Jose Formation. Sandstone and petrified wood were locally derived from Paleozoic, Mesozoic, and Cenozoic clastic stratigraphy; no distinction was made between recycled and primary sandstones or petrified wood. Limestone clasts were gray in color, occasionally fossiliferous, and assumed to be sourced from Paleozoic stratigraphy in the Sierra Nacimiento. One boulder of crystalline marble with large Crinoidea fossils was found to the south of Rio Gallina; the source of this boulder is unknown. Claystone and siltstone tended to be well indurated and infrequent in the gravel deposits except for deposit 10 **(Figure 8)** which was lithified by iron oxide (?) and contained abundant friable clay rip ups.

Figure 7—Quartzite gravel clast north of Rio Gallina with remnant matrix indicating re-working from a sedimentary formation or possibly that the gravel lag was a cemented deposit before being eroded.

Vein quartz was white to yellow in color and depending on the location of the Quaternary gravel deposit was inferred to be recycled from the San Jose Formation or a combination of both recycled clasts and clasts sourced from hydrothermal quartz veins in basement rock outcropping in the Sierra Nacimiento to the south. Chert and chalcedony were found in most deposits as either angular-rounded chert pebbles or angular chalcedony. Chalcedony was more abundant in the southern deposits.

Mafic and felsic igneous clasts included dioritic, gabbroic, granitic, and syenitic compositions. Clast counts were done quickly and no in-depth effort was made to decipher precise mineral percentages of igneous clasts. Due to the weathered and rounded nature of these clasts it is possible that some arkosic sandstone cobbles were mistaken for felsic igneous clasts. Very few volcanic clasts were found in the gravel terrace deposits; the clasts observed were porphyritic. The category 'other metamorphic' includes intermediate to high grade metamorphic rocks with phyllitic, schistose, and gneissic textures.

One possibility for some of the northern deposits is that they are not Quaternary in origin at all, but rather gravel lag remnants of an angular unconformity between basal San Jose Formation conglomerates and the underlying Paleogene or Cretaceous. At the unconformable angular contact between the Nacimiento Formation and the base of the San Jose Formation, the San Jose dips approximately west at moderately low angles. If this basal contact was projected eastward accounting for erosion during the Quaternary, the base would project onto the top of several hogbacks containing lag gravels. The possibility persists that these lag gravels are the remnants of the basal conglomerates of the San Jose Formation which dispersed, and scoured underlying bedrock, from east to west into the San Juan Basin during early Eocene time (Smith, 1988).

A lag gravel found at an anomalous height above modern grades was observed at 13S 335182m E, 4035560m N NAD83 and inferred to either be a remnant of the angular unconformity between Eocene strata and Mesozoic strata or from an anthropogenic origin. This deposit was found approximately 260 m above grade of the nearest continually channelized stream and was limited to quartzite, metaconglomerate, and sandstone clasts. Not enough clasts were found to reach the desired n=200 count at this location. This lag was mapped as a terrace gravel (**Qg**) despite uncertainty of its origin.

Sample 10 **(Figure 8)** was counted at a deposit just 40 m above modern grade in a deposit cut into a hogback of the Point Lookout Sandstone of the Mesaverde Group. This deposit was lithified, likely by an iron oxide, and contained an abundance of claystone and siltstone clasts compared to other deposits. The claystones and siltstones were extremely friable and tended to crumble when the lithified deposit was split open, leaving behind a cast of the rip-up. This claystone and siltstone lithology was observed, but not counted, in the Cuba Mesa Member and Llaves Member of the San Jose Formation. It is assumed that these fine-grained lithologies would have been found in other northern deposits had they not been weathered to a gravel lag consisting of only weathering resistant lithologies.

Figure 8—Lithified Quaternary terrace gravel (Qg).

UNIT DESCRIPTIONS

CENOZOIC

QUATERNARY

Anthropogenic

af **Artificial fill**—Unconsolidated clay, silt, and fine sands accumulated behind artificial dams or berms that raise local base level. Alluvial, eolian, and slope-wash input. Terminally drained; non-dissected planar surface; high organic content; sparsely to non-vegetated. Estimated thicknesses of deposits are 2–3 m.

Drainage Deposits

Ql **Lacustrine deposits**—Unconsolidated clay, silt, and very-fine lower sands in terminally drained ponds or shallow depressions. Abundant dark-brown organic content; minor eolian and slope-wash input. Terminally drained; non-dissected planar surface; sparsely vegetated. Approximate thicknesses of deposits are 0–4 m.

Figure 9—Naturally occurring Quaternary lacustrine deposit in the northwestern region of the French Mesa 7.5′ quadrangle. Controlled burns can be seen in the background.

Qar **Recent Alluvium**—Unconsolidated clays, silts, sands, gravels, and cobbles including active channel and floodplain and the lowest terrace surface. Found 0–3 m above modern channel grade. Deposits are approximately 1–4 m thick.

Qay **Younger Alluvium**—Unconsolidated clays, silts, sands, gravels, and cobbles forming an inactive alluvial terrace surface 3 to 8 m above channel grade. Deposits are approximately 4–9 m thick.

Qayr **Recent and Younger Alluvium**—See descriptions above for units **Qar** and **Qay**.

Qao **Older Alluvium**—Unconsolidated clays, silts, sands, gravels, and cobbles forming an inactive alluvial terrace surface greater than 8 m above channel grade. Deposits are greater than 9 m thick.

Qaf **Alluvial fan**—Unconsolidated clays, silts, sands, gravels, cobbles, and boulders forming fans grading and interfingering with adjacent Quaternary deposits. Cobbles, boulders, and gravels are predominately found in lenticular channels 1–2 m wide and less than 1 m thick; clast sizes up to 0.75 m. Fans have low relief and lack pronounced slope break at terminal end. Moderately to deeply incised by active channels; occasionally not incised. Occasional kinetic sorting and coarsening up debris flow levees from higher flow events. Deposits are approximately 10(?) m thick**.**

Qg **Terrace gravels—**Unconsolidated deposits of boulders, cobbles, and gravels of locally derived and exotic rock types. Commonly found as lag gravels on raised topographic surfaces or as deposits 2–3 m thick. On strath terraces or hillslopes 20–105 m above modern grade. Deposits occasionally found in light-red (5R 7/6) soils. At one location (13S 334700m E, 4027694m N NAD83), the matrix is lithified. Calcium-carbonate cement 0.5–2 mm thick on underside of pebbles, thickness increases with distance above modern grade. Clasts include subrounded locally derived sedimentary and recycled metamorphic clasts; subrounded to well-rounded, exotic sedimentary, metamorphic, and igneous clasts. Largest clasts are up to 0.35 m in diameter. May include pebbles and cobbles from rock types in immediate proximity of deposit. In the north half of the quadrangle, deposits are predominately locally derived sandstone, conglomerate, silty mudstone, vein quartz, chert, petrified wood, and recycled quartzite and metaconglomerate. Recycled quartzite is probably sourced from the San Jose Formation and it is possible that some lag gravels are remnants of an angular unconformity between the San Jose Formation and underlying Cretaceous strata. In the south half of the quadrangle **(Figure 10)**, deposits have the same clasts as those to the north plus other exotic-rock types. These include common felsic igneous, limestone, amphibolite, chalcedony; occasional limestone, schist, phyllite, mafic igneous, gneiss; rare porphyritic volcanic clasts. Deposits are less than 3 m thick.

Figure 10—Strath-terrace gravel deposit near the southern map boundary. This deposit featured abundant exotic lithologies within a 3-m-thick horizon.

Slope wash, Alluvial, and Eolian Deposits

Qas **Alluvium and slope wash**—Unconsolidated clays, silts, sands, and gravels with minor active alluvial channels and sloped floodplains with significant input from slope wash. Forms subdued topography with moderately to deeply incised channels, coarsening and sloping upwards towards hillslopes. Likely contains some portion of eolian sands and colluvial debris. Commonly has gradational contact with Qsa as alluvial incision and deposition gives way to smooth, slope-wash-dominated deposits. Estimated thicknesses of deposits are 1–5(?) m.

Qsa **Slope wash and alluvium**—Unconsolidated clays, silts, sands, and gravels in small basins and slopes dominated by slope wash, shallowly incised alluvial channels, and low-relief fans. Occasionally internally drained with negligible channelized inflow and outflow of alluvial material. Forms flat and sloped topography with nonexistent to shallowly incised channels. Coarsens and slopes upwards towards hillslopes. Contains a moderate portion of eolian sands and colluvial debris. Mapped from aerial imagery with supporting field observations. Estimated thicknesses of deposits are 1–5 m.

Qse **Slope wash and eolian deposits**—Unconsolidated clays, silts, and sands deposited on raised topographic positions or in small, shallow basins. Contain sheet-flow sediments sourced from hillslopes (i.e. slope wash) with input of windblown sediments. Dune forms are subdued but present; exhibits "bumpy" texture in LiDAR imagery. Margins of deposits may coarsen to pebble- and cobble-sized clasts transported by sheet flow from hillslopes. Where dune forms are not present, a veneer of thin, well-sorted, silt to very fine sand at surface indicates presence of wind-transported material. Found in proximity to Rio Gallina and its tributaries on adjacent alluvial terraces (13S 331668m E, 4028877m N NAD83) or nearby hillslopes (13S 330637m E, 4020377m N NAD83). Mapped from aerial imagery with supporting field observations. Deposit thicknesses are 0–2 m**.**

Mass-wasting Deposits

Qcu **Colluvium, undivided**—Unconsolidated boulders, cobbles, gravels, sands, silts, and clays forming thick, incised, mantles on hillslopes; mantles are not incised on sub-horizontal low relief surfaces. Deposits include material from colluvial processes and undefined mass wasting that may include fall, topples, slides, spreads, and flows. Include a variety of locally derived rock types; occasionally dominated by one rock type when source area is limited, usually adjacent to hogbacks. In the northeast part of the quadrangle (on the eastern side of an unnamed arroyo, ≈1.5 km west of Archuleta Arroyo) some areas mapped as **Qcu** appear to be small, distal remnants of either landslides sourced from the west or alluvial fans sourced from the east. These deposits are unexposed but are identified by large (up to several meter) sandstone blocks and pebbles overlying Mancos Shale. Clast sizes are up to 5 m in diameter. Calcium-carbonate cement (1 mm thick) found on the underside of clasts. Deposition predates incision of drainages; lacks landslide scarps, toes, and other defining morphological features. Colluvium is only mapped where the deposits obscure underlying bedrock. Deposits are 1–20 m thick.

Qlsy **Younger landslides, undivided**—Unconsolidated rock and sediment moved by mass-wasting processes with fresh morphological features; includes falls, slides, and flows. Consists of jumbled and deformed, locally derived rock types. Slides include translational and rotational types that are commonly responding to local, recent incision. Rock-fall surfaces are still fresh and unweathered. Deposits create mantles preventing erosion of underlying bedrock. Defined scarp, lateral margins, and toes; commonly back-rotated; moderately to very hummocky; nonexistent to minor incision. Small areal extent. Minor colluvial, slope wash, and alluvial input. Deposits are approximately 0–4 m thick.

Qlso **Older landslides, undivided**—Unconsolidated rock and sediment moved by mass-wasting processes with obscured morphological features. Consists of jumbled and deformed, locally derived rock types. Undefined and typically unrecognizable mode of downslope transport. Likely responding to wetter climatic conditions during glacial intervals and base-level fall in the valley floor from incision of the Rio Gallina drainage, which is a tributary to the

Rio Chama. Clast sizes are up to 5 m in diameter. Scarps poorly defined, gradational lateral margins; smooth to moderately hummocky; moderately to deeply incised; occasionally back-rotated with Toreva blocks (Reiche, 1937) up to 250 m in size. Large areal extent. Moderate to abundant alluvial, colluvial, and slope-wash input. At one location (13S 341954m E, 4028202m N NAD83), there is a deposit with no source area for the sliding, this deposit is inferred to be Neogene in age. Deposits are approximately 0–20 m thick**.**

NEOGENE

PALEOGENE

PEs **San Jose Formation (Eocene)—**The San Jose Formation consists of two sandstone-dominated members and two mudstone-dominated members. We follow the stratigraphy defined by Smith (1992a). Total thickness ranges from 287–616 m in the Llaves quadrangle (Smith, 1988).

PEst **Tapicitos Member (Eocene)—**This member is exposed along the western edge of the map. The unit is composed of brick-red to red siltstone interbedded with green, brown and tan siltstone and lenticular, white, sandstone beds that are similar in texture and composition to the underlying Llaves Member (see next entry). The Tapicitos Member is coarser than the older mudrock unit, the Regina Member (Smith, 1988). The medium- to coarse-grained sandstone beds range from 1.5–10 m in thickness (Smith, 1988). Pedogenic carbonate nodules are locally found in some red-siltstone intervals. The lower contact was drawn using a combination of LiDAR and satellite imagery at the top of the highest, thick, Llaves sandstone beds. Similarity between sandstones in the various members of the San Jose Formation, lateral variability, poor exposure, and gradational and/or interfingering of the members add considerable uncertainty to the placement of this contact. This unit is interbedded with the Llaves Member and the top is eroded in this area. Paleocurrent measurements indicate flow toward the west and southwest (Smith, 1988). Up to 135 m thick regionally (Hobbs and Pearthree, 2021), maximum exposed thickness in the map area is 150 m, but in most places only 90 m is preserved (Baltz, 1967).

PEsl **Llaves Member (Eocene)—**This member covers the northwestern part of the quadrangle and is mainly composed of white to yellow, coarse- to fine-grained, poorly sorted arkosic sandstone to gravelly sandstone; the sand grains are subangular to subrounded. The gravel size generally ranges from granules to small pebbles (1–10 mm), but some intervals on the east side of the exposure contain pebbles to cobbles up to 15 cm in diameter. The well-rounded to subrounded gravel is predominantly light-gray to brownish-gray quartzite, with less amounts of metaconglomerate, vein quartz, and yellow and tan sandstone. The sandstone is coarsest along the east side of the exposure and becomes finer toward the west. The 3-to-20-m-thick, stacked, sheet sands are frequently separated by thin (1–5 m), red-siltstone intervals. Green, red, or brown mudstone rip-up clasts are common at the base of the channels. The sandstones display trough cross-bedding, low-angle laminar cross-bedding, and laminated to massive bedding. Paleocurrent measurements indicate flow toward the west and southwest (Smith, 1988). Gradational interfingering with overlying Tapicitos Member and intertongues with the underlying Regina Member (Hobbs and Pearthree, 2021). 95–135 m thick regionally (Hobbs and Pearthree, 2021), maximum thickness is 213 m at the type-section (Baltz, 1967).

PEsr **Regina Member (Eocene)—**This unit is best exposed in the badlands escarpment just east of the Continental Divide in the southwestern corner of the map area, in the headwaters of Arroyo Blanco and Arroyo Almagre **(Figure 11)**. The unit consists of variegated red, white, green, and olive-brown, fine-grained, poorly cemented sandstone, mudstone, and siltstone intercalated with yellow, white, and gray medium- to coarse-grained, well-cemented, lenticular, ledge-forming sandstones exhibiting fining-up sequences. Poorly cemented sandstones occasionally found as either deep (1–2 m) and narrow (2–3 m) channels or stacked channels that are thin (<0.5 m) and wide (>20 m). Bedding is tabular to cross-bedded. Mudstones have waxy texture, mottled coloring, are well-indurated, micaceous, and contain minor to moderate silt and occasional very fine sand content. The unit is thicker and coarser to the south. Paleocurrent measurements indicate flow toward the south (Smith, 1988). In this area, the Regina Member is interbedded with both the Cuba Mesa and Llaves members (Smith, 1992). The member is 175–500 m thick (Baltz, 1967).

Figure 11—Colorful beds of claystone, siltstone, and sandstone in the Regina Member of the San Jose Formation.

PEsc **Cuba Mesa Member (Eocene)**—This member is a thick, cliff-forming, tan to yellow sandstone to gravelly sandstone. The arkosic sandstone is medium- to very coarse-grained; the sand grains are angular to subrounded, with subangular grains predominating. At one locality, a 5–20 cm thick zone about 1–1.5 m above the base has clasts of fine-grained Nacimiento mudstone and gravel (quartzite, quartz, chert), mixed with green siltstone. Upsection, the gravel is scattered. The sandstone is massive to laminated or cross-bedded. Paleocurrent measurements indicate flow toward the south (Smith, 1988). A thin, sandy shale belonging to the Regina Member separates the Cuba Mesa Member from the Llaves Member north of Cañoncito de las Yeguas. South of Cañoncito de las Yeguas, a much thicker interval of Regina Member separates the Cuba Mesa Member from the Llaves Member. The Cuba Mesa Member is complexly intercalated with the Regina Member near the south-central map boundary. The basal contact is at the bottom of a thick laterally continuous sandstone. The unit is approximately 100 m thick (Baltz, 1967).

PEn **Nacimiento Formation (Paleocene)**—Baltz (1967) recognized three informal intervals in this unit. The lower part of the Nacimiento Formation is red and green mudstone interbedded with sandstone, fine-grained sandstone and siltstone, white trough cross-bedded sandstone, and sandy mudstone. Sandstones are very fine- to coarse-grained, angular to subangular, poorly sorted, friable to moderately indurated; lightly calcium-carbonate cemented; occasional per-mineralized bark casts and mud rip-ups. The middle section is poorly exposed and composed of gray to green shale and lenticular sandstone beds. The upper section is primarily gray, fine- to coarse-grained, gravelly trough cross-bedded sandstone with lesser amounts of gray and brown mudstone and siltstone. Sandstones are occasionally olive-green to yellow-brown (5Y 4/4 to 5Y 5/6), angular to subangular, very fine- to coarse-grained, micaceous, and weakly cemented by calcium carbonate. Gravelly sandstone with orange-weathering, brown pebbles up to 1 cm and clay rip-up clasts up to 3 cm, sand matrix is medium- to very coarse-grained, poorly sorted, angular to subrounded, moderately to well-indurated. Interbedded with slope-forming, medium-grained sandstone, minor siltstone horizons, and mudstones. Siltstones are gray-weathering, tan to yellow, subrounded and moderately sorted with abundant plant fragments. Mudstones are light-gray to brown, waxy, with minor silt content and laminated with horizons of high sand content. The grain size in the Nacimiento Formation generally decreases to the south and paleoflow was toward the south (Smith, 1988). In this area, the lower contact is conformable and is marked by thin-bedded, flaggy sandstone above the thick, cliff-forming sandstone beds of the Ojo Alamo Sandstone. The top contact with the San Jose Formation is erosional with channels cutting into the underlying Nacimiento sandstones. Shales in the top of the Nacimiento Formation are gray and olive-green, whereas shales in the San Jose Formation are red and light green (Baltz, 1967). The unit is 180–380 m thick (Baltz, 1967; Fitter, 1958).

PEoa **Ojo Alamo Sandstone (Paleocene)—**White to tan, fine- to coarse-grained, stacked sandstones that are poorly sorted and angular to subrounded; interbedded with thin, sandy siltstone and silty mudstone. Commonly micaceous. Occasionally calcium-carbonate cemented. This sandstone forms prominent tan cliffs on hogbacks above the Fruitland Formation. Green mudstone rip-up clasts are common at the base of channels. Deciduous plant debris and muscovite are locally present. Interbedded, waxy, light- to dark-gray silty mudstone and silty to fine-grained light gray to green sandstone with flaggy bedding underlie poorly exposed, slope-forming beds up to 15 m thick. Silicified petrified wood is abundant; rare carbonized wood fragments are present. Sedimentary structures include trough to low-angle cross-bedding and laminated to massive bedding; occasional soft-sediment deformation. The basal contact is sharp and is unconformable. The top grades into the Nacimiento Formation. The unit is 14–30 m thick (Fitter, 1958; Baltz, 1967; Crouse et al., 1992); 30–75 thick in petroleum wells.

MESOZOIC SEDIMENTARY ROCKS

CRETACEOUS

Kkf **Kirtland-Fruitland Formation (Late Cretaceous)—**Although the Kirtland Formation has been removed by erosion in this area (Fassett and Hinds, 1971), we use the formal name (including both the Fruitland and Kirtland Formations) of the unit in this report. This unit has a lower and an upper section (Baltz, 1967). The lower beds are characterized by carbonaceous shale or low-quality coal that is interbedded with green siltstone, olive-gray, black, and gray silty shale, and thin white sandstones; the sand grains are angular to subangular. The green siltstone contains abundant muscovite in places. Discontinuous sandstone lenses are preserved high in the section in a few hogbacks in the northern and central parts of the quadrangle; the sand grains are angular. Two sandstone beds (0.5 to 6 m thick) located a few meters below the upper contact with the Ojo Alamo Sandstone in the northernmost Fruitland hogback are tan to white to greenish-white, fine- to medium-grained, and are poorly sorted. Bedding is massive to cross-bedded; carbonaceous material and muscovite are present in the upper bed. The sandstones high in the section in the Fruitland hogbacks in the central part of the quadrangle are white to yellow, medium- to coarse-grained, are poorly sorted, and are weakly to moderately cemented. Petrified wood replaced by silica or hematite is present. The contact at the base of the unit is conformable and the overlying contact is an erosional unconformity. The unit is 12–120 m thick (Fitter, 1958; Baltz, 1967; Crouse et al., 1992); 12–45 m in petroleum wells.

Kpc **Pictured Cliffs Sandstone (Late Cretaceous)**—Thin beds of tan to gray sandstone, tan siltstone and black shale. A landslide scar exposure of Pictured Cliffs Sandstone near the northern boundary of the map reveals sandy to silty shale and thin-bedded, fine-grained sandstone with carbonaceous plant debris (Baltz, 1967). Fitter (1958) describes discontinuous exposures of Pictured Cliffs Sandstone on the northwest side of French Mesa. The sandstone is gray to tan, fine- to medium-grained, with massive bedding and burrows of Halymenites major. The Pictured Cliffs Sandstone is thin in the southern part of the map area; Baltz (1967) lumped this unit into the Fruitland-Kirtland Formation. In the west-central part of the Llaves quadrangle, the Pictured Cliffs is a shale with thin beds of siltstone and fine-grained sandstone and carbonaceous plant debris exposed in a landslide scar. Baltz (1967) mapped this sandy shale as part of the Lewis Shale in the northern Llaves quadrangle. Fassett and Hinds (1971) note that the Pictured Cliffs Sandstone is commonly capped by a hard, iron-cemented, sandstone layer <0.5 m thick. The contact is usually placed at the top of the highest *Ophiomorpha*-bearing sandstone. The unit is 10–18 m thick (Fitter, 1958; Baltz, 1967); 14–52 m in petroleum wells.

Kl **Lewis Shale (Late Cretaceous)**—Light-gray to dark-gray shale with minor intercalated siltstone, fine-grained sandstone, and limestone concretions. Upper part of the formation is interbedded with well-indurated, orange-brown, sandy siltstone with light calcium-carbonate cementation. In the middle of the formation, shale is dark-brown to dark-gray, weathering light-gray, and friable, with minor silt content. Contains discontinuous lenses of dark-gray, weathering orange, finely laminated siltstone containing abundant Baculites sp. casts. Thin sandstone layers are common in the lower part of the section; these beds grade laterally into the La Ventana Tongue of the Cliff House Sandstone. Some of the thin sandstone beds grade laterally into layers of fossiliferous limestone concretions. The contact with the overlying Pictured Cliffs Sandstone is gradational and conformable. Unit is often distinctive at surface due to abundant, angular fragments of concretions that disintegrate on weathering. Unit thickness is 580 m (Fitter, 1958; Baltz, 1967); 446–660 m in petroleum wells.

Kmv Mesaverde Group (Late Cretaceous)—The Mesaverde Group includes the Cliff House Sandstone, the Menefee Formation, and the Point Lookout Sandstone.

Kch La Ventana Tongue of the Cliff House Sandstone (Late Cretaceous)—Gray, tan- to orange-brown sandstone, interbedded with sandy siltstones and thin layers of gray shale. The lower part of the unit is medium-grained and thickly bedded. The upper part is fine- to medium-grained, tan to orange-brown sandstone that is thinner-bedded and contains gray shale. Common trace fossils and calcium-carbonate cement. The upper contact with the overlying Lewis Shale is gradational. The unit is 33 m thick (Fitter, 1958); 26–64 m in petroleum wells**.**

Kmf Menefee Formation (Late Cretaceous)—Light-gray to dark-gray, carbonaceous shale intercalated with coal, ironstone, and mottled-white, gray, and brown sandstone-beds **(Figure 12)**. Sandstones are lenticular, very fine- to coarse-grained with planar-laminated bedding and occasional mud rip-ups. Coal found in lenticular beds (0.2–8m thick), has variable grade but is typically lignite, has minor clastic silt-content and amber; grades upwards into carbonaceous shales. Ironstone horizons are thin and nodular. The upper contact with the overlying Cliff House Sandstone is gradational and placed at the top of the highest coaly or shaly beds underlying continuous sandstones of the Cliff House Sandstone. The unit is 115 m thick (Fitter, 1958); 48–115 m in petroleum wells.

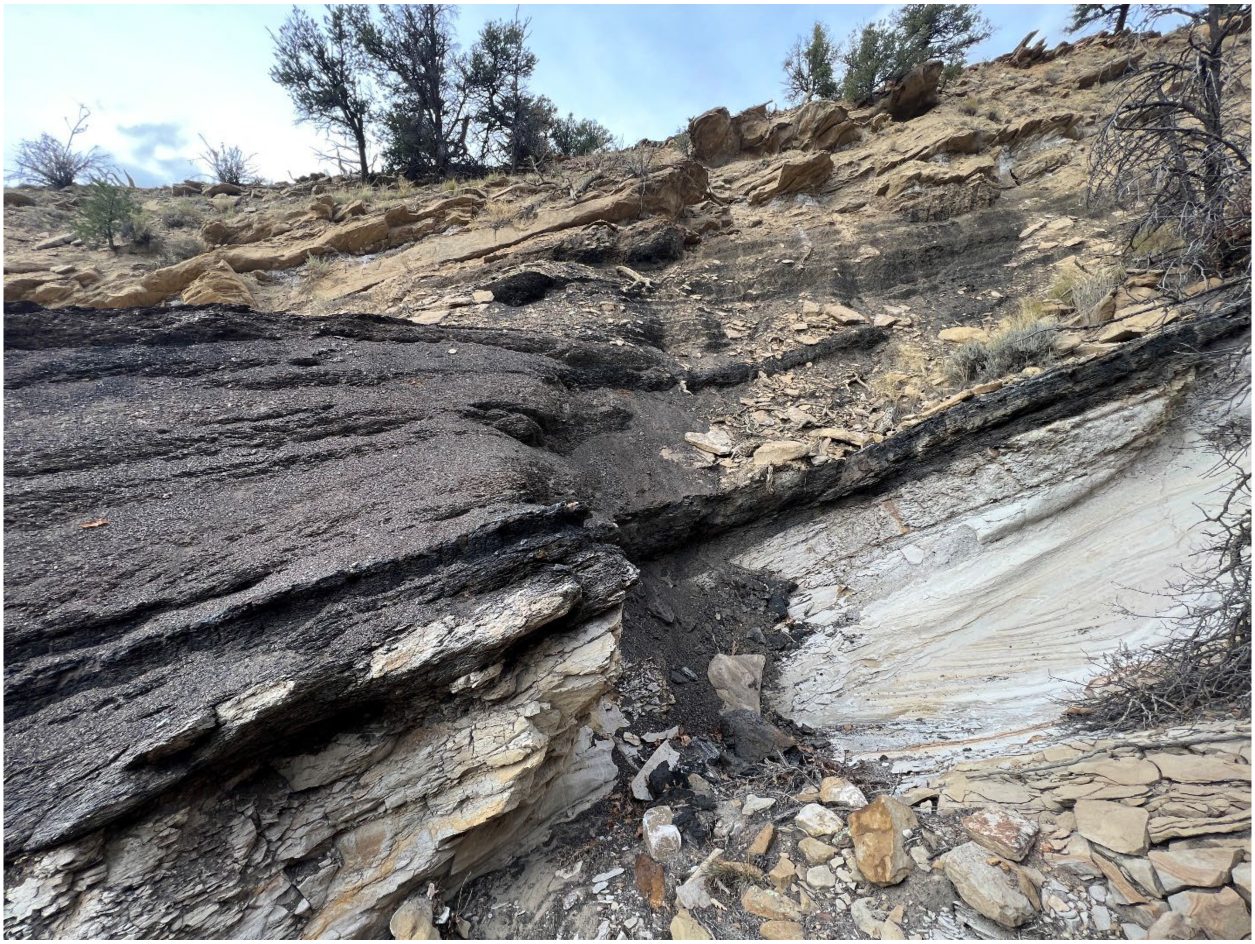

Figure 12—Thick coal sequence in the Menefee Formation.

Kpl **Point Lookout Sandstone (Late Cretaceous)**—Gray to tan, medium- to fine-grained, well-sorted sandstone with shale beds and trace muscovite. The sand grains are angular to subangular. The basal contact is gradational with the underlying Mancos Shale and the upper contact is sharp and conformable. The unit is 29 m thick (Fitter, 1958); 31–81 m in petroleum wells.

Km **Mancos Shale (Late Cretaceous)**—The Mancos Shale was originally defined for exposures near Mancos, Colorado (Cross and Purington, 1899). This unit is extensively exposed across the west-central United States, is laterally variable, and has a commensurately complex and variable nomenclature. We divide the Mancos Shale into a basal Graneros Shale (the Clay Mesa Member of Aby et al. (2016) is not distinctive on this quad) overlain by the Greenhorn Limestone Member, which is in turn overlain by the Carlisle Member that contains (on this quadrangle) the Juana Lopez Member (**Figure 13**). A significant unconformity separates the El Vado Sandstone and the upper part of the Mancos Shale (equivalent to the Niobrara Formation in the mid-continent) from the lower part of the shale. The El Vado Sandstone is intermittently exposed on this quadrangle due to erosion and/or burial by landslides, colluvium derived from erosion of thick shales, and alluvium.

Figure 13—View of Rio Gallina flowing through Cretaceous stratigraphy. Upper Dakota Formation beds creating hogback in foreground, isolated white hogback of Greenhorn Shale Member, discontinuous hogbacks of the Lower Carlisle Shale Member, and prominent hogback of the Juana Lopez Member of the Mancos Shale.

Kmu **Upper Mancos Shale (Late Cretaceous)**—Poorly exposed gray shale forming slopes below the Point Lookout Sandstone. Equivalent to the Niobrara Formation in the mid-continent (Ridgely et al., 2013; Cheney, 2018). The unit is 291–375 m thick in petroleum wells.

Kme **El Vado Sandstone (Late Cretaceous)**—This relatively thin sandstone interval within the upper Mancos Shale is composed of sub-centimeter to ≈5 cm beds of limey, quartz-rich, sparsely to abundantly fossiliferous, very fine- to medium-grained, moderately well-sorted, sometimes ripple-laminated sandstone beds separated by 1–15 mm shale intervals. Forms prominent hogbacks near the confluence of the Rio Gallina and Chupadero Arroyo (**Figure 1**). The upper and lower contacts are mapped at the lowest and highest exposed sandstone beds. In many other localities within the quadrangle, the El Vado Sandstone is either absent or not exposed, although it is thought to be fairly continuous within the San Juan Basin, although variable in specific detail (Cheney, 2018). This unit lies above a significant unconformity and is about 6 m thick where exposed; 87–125 m thick in petroleum wells.

Kmcu **Upper Carlisle Shale (Late Cretaceous)**—This poorly exposed, black-shale interval lies below a significant unconformity and above the Juana Lopez Member (Ridgely et al., 2013; Cheney, 2018). The shale is 104–178 m thick in petroleum wells.

Kmjl **Juana Lopez Member (Late Cretaceous)**—The Juana Lopez is a regionally distinctive interval of yellow to reddish-brown, weathering grey, thinly bedded, sometimes ripple-laminated, shelly, recrystallized limestone to sandy limestone with thin shale and sandy siltstone interbeds. Sandy limestone to calcareous sandstone very fine- to fine-grained, subangular, well-sorted, iron-stained, finely laminated (up to 2–5 cm), lightly to heavily bioturbated. Contains abundant shell casts, minor mud clasts, and occasional hummocky ripples. Sandy siltstone orange and gray, weathering tan to buff, sand portion very fine- to fine-grained, subangular, moderately sorted, subrounded, thinly laminated (0.25 cm) to thinly bedded (7.5 cm), Calcium-carbonate cemented, interbedded with sandy limestone. Shell hash horizons up to 1 cm thick, recrystallized, and contain occasional 3 mm ooids. Lower and upper contacts on this quad are the lowest and highest, locally continuous, limestone beds. Thin limestone beds and lenses are sometimes found up to 15 m above the top and below the base. Weathers to distinctive platy fragments containing sparse to common shell fragments, burrows, and ripple marks. Outcrops of the Juana Lopez Member tend to be sparse but sometimes form hogbacks. The unit is 30–34 m thick in petroleum wells.

Kmcl **Lower Carlisle Member (Late Cretaceous)**—The lower Carlisle Member is composed of monotonous dark-grey to black shale, weathering light-gray, with brown-red and tan-yellow weathering patina. Shale has minimal silt content and contains locally abundant septarian nodules. Sometimes slightly shelly, laminated to very thin-bedded shale and locally(?) hard, platy-weathering siltstone. Unit is generally poorly exposed and forms strike valleys. Lower contact is the top of the uppermost continuous limestone of Kmgh, and the upper contact is the base of the Juana Lopez Sandstone. Thickness of the unit is 100 m.

Kmgh **Greenhorn Limestone (Late Cretaceous)**—Characteristic light-grey to white-weathering limestone interbedded with shale, silty shale, and silty sandstone. Shales gray-weathering, pale-brown to light-gray, occasional shell fossils (Inocermidae sp.) and thin shell-hash horizons, 0.5–1 cm laminations within 0.25–1 m horizons, calcium carbonate. Chalky limestone intervals, white weathering to pale-gray, 0.2–1 m thick, planar-bedded. Silty sandstone, gray, weathering yellow to orange, planar-laminated, subangular, well-sorted, silty to fine-grained, abundant shell fossils, occasional bioturbation, 1–5 cm thick beds, calcium-carbonate cement, weathering pits. The unit is about 10 m thick at the surface; 23–43 m thick in petroleum wells.

Kmg **Graneros Member (Late Cretaceous)**—Generally poorly exposed, grey to black, sometimes calcareous, platy to laminated, fossiliferous, sometimes contains concretions, slope-forming shale. The unit is 53 m thick (Fitter, 1958). 14–39 m thick in petroleum wells.

Kd **Dakota Formation (Late Cretaceous)**—(includes the Encinal Canyon, Cubero, and Paguate Members and the Oak Canyon and Clay Mesa Members of the Mancos Shale; Owen et al., 2005). The oldest unit, the Encinal Canyon Member, is a tan fine- to medium-grained, moderately to well-sorted, quartz sandstone with thin to medium tabular-bedding that is locally cross-bedded. The grains are subrounded to angular. Asymmetric ripple marks are common. This sandstone contains fossil wood and carbonaceous plant impressions are common near the base. The Cubero Member is fine- to medium-grained and well-sorted. This sandstone has thin to medium tabular-bedding and is usually bioturbated. The Paguate Member is fine- to medium-grained and well-sorted. This sandstone has thin to medium tabular-bedding and is usually bioturbated. Symmetrical ripple marks are locally present. Abundant 0.5–1 mm, brown-orange, iron-oxidation spots. Occasional herringbone cross-bedding and calcium carbonate cement. The intervening shale beds are variably carbonaceous and black or form thinly bedded, gray sandstone and black shale intervals. In the southern part of the map, the Dakota consists of two, thick, sandstone intervals separated by 2–3 m of shale. The unit is 30–35 m thick.

Kbc **Burro Canyon Formation (Early Cretaceous)**—White, light-yellow, orange, and buff, conglomeratic sandstone with thin lenses of green or, more rarely, red mudstone (Saucier, 1974). The sandstone is fine- to medium-grained, quartzose, and kaolinitic. Small-scale trough cross-bedding is associated with the conglomeratic channels. Conglomerate clasts are mostly chalky, white chert with varicolored quartzite and chert pebbles up to 2.5 cm in diameter; occasionally clast supported. Larger clasts tend to be well-rounded while small clasts are fragmented and angular. Gravel is common near the base of the unit and is rare near the top of the unit. Laminar, low-angle wedge and high-angle planar wedge cross-bedding is common in the sandier portions of the formation. Some sandstone beds are massive. Occasional asymmetrical ripples, pitted texture, wood casts, and iron-cemented sandstone concretions (0.5 cm in size). Slope-forming mudstone horizons are 0.5 to 3 m thick, gray-green, black, or brown-orange, and calcium-carbonate cemented. Basal contact disconformable with significant paleotopography. The unit is 25 to 30 m thick, thinning toward the south.

Jm **Morrison Formation (Late Jurassic)**—Two members of Morrison Formation, the Brushy Basin and the Westwater Canyon Sandstone members, are exposed in the Llaves area.

Jmb **Brushy Basin Member (Late Jurassic)**—This member is comprised of variegated light-greenish-gray, light-gray, grayish-yellow-green, light-olive-gray, yellowish-brown, and drab-reddish-brown, bentonitic mudstones with discontinuous beds of cross-bedded to massive, white, yellow, tan or grayish-tan sandstone **(Figure 14)**. Mudstones have moderate silt and minor very-fine sand content; occasional yellow patina and pedogenic carbonate nodules. Occasionally very well-indurated. The sandstones are fine- to coarse-grained and poorly to moderately sorted; the grains are angular to well-rounded. Occasional green rip-up clasts, silica cement, burrows, and large (2–4 m) spherical, iron-cemented, sandstone concretions. The iron-bearing minerals in these sandstones are commonly altered to 2–4 mm oxidation spots, giving the sandstones a speckled appearance on weathered surfaces. Channels are laterally discontinuous, stacked, and increase in abundance and stratigraphic proximity to the south. Basal contact conformable but abrupt with underlying Westwater Canyon Member of the Morrison Formation. Upper contact with overlying Burro Canyon Formation is sharp and disconformable with significant paleotopography. The unit is up to 50 m thick.

Figure 14—Brushy Basin Member of the Morrison Formation (slope former with green undertones, mostly covered by colluvium), overlain by red and yellow Burro Canyon Formation which is in turn overlain by orange-weathering Dakota Formation.

Jmw **Westwater Canyon Member (Late Jurassic)**—A thick, white to buff, ledge- and cliff-forming, laminated to trough cross-bedded sandstone with occasional conglomeratic sandstone, and abundant horizons of mudstone rip-up clasts is preserved at the base of the Morrison Formation in the eastern part of the quadrangle (**Figure 15**). Channel forms are common. The sandstone is fine- to coarse-grained and is poorly sorted; the sand grains are angular to well-rounded. Feldspar is usually altered to clay, forming either white clay-clots or weathered to form a pitted texture. Common orange oxidation spots. Occasional heavy mineral laminations, calcium-carbonate cement, burrows, and rounded carbonate nodules. Conglomeratic sandstone is moderately friable with clasts of quartz, chert, and mudstone. Intervals of red and green, silty mudstone rip-up horizons reach 6– 8 m above base while isolated rip-ups are found throughout; commonly scoured by sandstone channels. Variable thickness throughout quadrangle, thin or locally absent to south-southeast. Basal contact is conformable, gradational, and interfingering with underlying Bluff Formation sandstones. Upper contact abrupt but conformable with overlying Brushy Basin Member of the Morrison Formation. Ranges from 0 m, between channels, to 75–100 m thick in channels.

Figure 15—Sandy siltstone rip-up horizons in the Westwater Canyon Member of the Morrison Formation.

Jsb Summerville and Bluff Formations undivided (Middle to Late Jurassic)—The Bluff Sandstone is a slope-forming, pinkish-tan, very fine- to medium-grained, well-sorted, friable, eolian sandstone with cross-beds in thick sets. A distinct rock type composed of maroon, pale-brown, grayish-red, fine-grained sandstone and mudstone that is too thin to map separately overlies the eolian sandstone. Upper contact grades into and interfingers with the overlying Westwater Canyon Member of the Morrison Formation. The Summerville Formation below the Bluff interval is thinly and cyclically bedded, drab-maroon to grayish-red or white to gray sandstone, siltstone, and sandy siltstone (**Figure 16**). Sandstones white- to gray-weathering, tan to peach or brown to red, very fine- to medium-grained, poorly to moderately indurated with platy or flaggy bedding. These sandstones are found in 5–10-cm-thick beds with 0.25–1 cm laminae; occasionally calcium-carbonate cemented, creating botryoidal weathering patterns. Siltstones are red, green, and white with variable clay and sand content, occasionally scoured by sandstones. A white to yellowish-gray sandstone that overlies the Todilto Formation at the base of the Summerville contains a bed of micritic, light-gray limestone. Thickness of the unit is 100–125 m.

Figure 16—At sloped plateau in foreground, red beds of Summerville formation grade into eolian sand beds of the Buff Formation and overlain by the Westwater Canyon Member of the Morrison Formation (yellow-tan, cliff-forming unit at top of sloped plateau).

Jet (Jt and Je) Todilto Formation and Entrada Sandstone (Middle Jurassic)—(These units are usually cliff-formers north of the Rio Gallina, so the units are lumped in the northeast corner of the map area; mapped separately on French Mesa). The Todilto Formation consists of a lower, limestone-dominated interval (Luciano Mesa Member) overlain locally by a gypsum interval (Tonque Arroyo Member) (Lucas et al., 1985; Kirkland et al., 1995). The Luciano Mesa Member is 2–8 m thick and consists mostly of thinly laminated, dark-gray or yellowish-gray, kerogenic limestone and calcareous shale. Found in laminations (0.25–1 cm thick). The overlying Tonque Arroyo Member is up to 38 m of white to light-gray, finely crystalline to megacrystalline gypsum interbedded with carbonate. A limestone microbreccia left by dissolution of the gypsum of the Tonque Arroyo Member is present at several places above the Luciano Mesa Member. Total Todilto Formation thickness is up to 46 m **(Figure 17)**. The Entrada Sandstone is a yellow, grayish-orange and red, cross-bedded and ripple-laminated, cliff-forming sandstone. The Entrada Sandstone is a very fine- to medium-grained, moderately well-sorted sandstone that forms bold cliffs along escarpments and mesa tops. Top is conformable and the base is an unconformity. The unit is 55–75 m thick (Fitter, 1958; Crouse et al., 1992).

Figure 17—Upper portion of cross-bedded eolian Entrada Sandstone overlain by beds of the Todilto Formation limestone and gypsum along the Rio Gallina in the east-central map area.

TRIASSIC

TRc **Chinle Group**—The Chinle Group is divided into two informal subdivisions (upper and lower) and the medial formal formation, the Poleo Sandstone.

TRcu **Upper Chinle Formation (Late Triassic)**—An informal upper unit that includes slope-forming mudstone of the Painted Desert Member of the Petrified Forest Formation. The Rock Point is not exposed. The Petrified Forest Formation, which is a reddish-brown bentonitic mudstone that forms extensive slopes and dissected badland areas where exposed, consists of two members, the Painted Desert Member and the Mesa Montosa Member. The overlying Painted Desert Member is reddish brown, bentonitic mudstone and thin ledges and lenses of ripple-laminated or cross-bedded sandstone. Petrified wood is common. Its base is a thick mudstone bed above the highest sandstone ledge of the Mesa Montosa Member. The lower Mesa Montosa Member is primarily sandstone, with lesser amounts of mudstone and siltstone that range in color from reddish-brown to green; the sandstone beds are very fine-grained to fine-grained, lightly calcium-carbonate cemented, micaceous and typically ripple-laminated to thinly-laminated, producing flaggy bedding. Ripples are asymmetric. The Mesa Montosa Member forms a ribbed slope, 4–24 m thick, between coarser-grained Poleo Formation sandstone below, and slope-forming mudstone of the Painted Desert Member of the Petrified Forest Formation above. The top and bottom are sharp contacts. The Entrada Sandstone was deposited on the J-2 unconformity surface that separates the Chinle and Entrada (Lucas, 1993). The Petrified Forest Formation is 176 m thick, north of the Rio Gallina (Lookingbill, 1953).

TRcp **Poleo Member of the Chinle Formation (Late Triassic)**—Yellow-brown, yellow-gray, white and red sandstone, conglomeratic sandstone, conglomerate, silty sandstone, and mudstones. Sandstones are quartzose, fine- to medium-grained, angular to subangular, micaceous, and cross-bedded. Sandstones contain occasional rip-up clasts, potassium feldspar, mica, and plant imprints. Commonly exhibits honeycomb weathering and is found in well-indurated beds less than 1 m thick with tabular to trough cross-bedding. The conglomerate in the Poleo Formation is often black or mottled-red and white and contains siltstone, nodular calcrete, chert and quartzite clasts. The matrix includes abundant potassium feldspar and exotic lithics, including fine-grained sedimentary, low-grade metamorphic, and felsic igneous clasts; commonly calcium-carbonate cemented. Conglomerate is interbedded with horizons of very coarse sandstone. The conglomeratic sandstone is well-rounded, well-indurated, calcium-carbonate cemented and has quartz, chert, and sedimentary clasts up to 7 mm in diameter. Silty sandstones are gray to blue, weathering gray, with abundant silt and minor very fine sands; thinly laminated and micaceous. Shales are brown-weathering, purplish- to brownish-maroon with minor silt content; micaceous and slope forming. This unit forms prominent light-colored cliffs. The base of the unit is sharp (corresponds to the Tr-4 unconformity of Lucas, 1993) and the upper contact is gradational into the overlying Mesa Montosa Member of the Petrified Forest Formation. The Poleo Member is about 25–54 m thick on French Mesa (Crouse et al., 1992).

TRcl **Lower Chinle Formation (Late Triassic)**—An informal lower unit that contains the Salitral Formation and the Agua Zarca Sandstone. The Salitral pinches out northward on French Mesa, is absent in the Rio Gallina dome, and is about 13 m thick in the Gallina Mountain dome. The Salitral Formation is red shale on French Mesa and is maroon to red siltstone in the Gallina Mountain dome. This unit is poorly exposed. The white conglomeratic, quartz-rich, coarse-grained sandstone beds with quartz pebbles that comprise the Agua Zarca in the Chama Basin to the east of the map area are absent to thin (1 to 2 m) in this area. Salitral is 10–13 m thick (Fitter, 1958); maximum unit thickness up to 15 m.

PALEOZOIC SEDIMENTARY ROCKS

PERMIAN

Pc **Cutler Formation (Early Permian)**—Red, maroon, and white siltstones, arkosic sandstones and minor intraformational and extraformational conglomerates are exposed on the east side of the quadrangle. Sandstones and conglomerates found in isolated lenticular-channel bedforms. The sandstones are mottled-white and orange-red to maroon, weathering gray to red-brown, medium-to very coarse-grained, angular to subangular; contain abundant feldspars, metallic minerals, and lithics; calcium-carbonate cemented; flattened, green, mud rip-ups found at base of channels. Occasional soft sediment deformation. The gravels are usually well-rounded and pebble-sized, but occasionally as large as 20 cm in diameter, and include chert, Proterozoic granitic rocks and quartzite. Common per-mineralized *Calamites* sp. casts found in conglomerate horizons. The siltstones are thick, slope-forming units with abundant calcrete nodules between thin sandstone sheets that are massive to trough cross-bedded. Exposures in the east-central part of the map area are predominantly siltstone with very few arkosic sandstones. The sandstones in this area range from fine- to very coarse-grained, and the gravelly lenses include chert and quartz pebbles and granules. The unit is 100–440 m thick (Fitter, 1958; Lookingbill, 1953).

PENNSYLVANIAN

IPm **Madera Formation (Pennsylvanian)**—Pennsylvanian rocks are exposed in a small outcrop in the northeastern part of the quadrangle. The base of the exposure reveals a green, medium-grained, arkosic sandstone with biotite that is overlain by a red, biotite-bearing, medium-grained, well-sorted arkose. A thinly bedded, green, very fine- to fine-, well-sorted sandstone with little feldspar lies above the arkose beds. Above the thinly bedded unit is a 3–4-m-thick sandstone that is massive at the base and cross-bedded at the top. This arkosic sandstone is fine- to medium-grained and well-sorted. A 3–4-m-thick sandy limestone with marine fossils, including crinoid stems, overlies this arkosic sandstone. A poorly exposed, yellow, arkosic, medium-grained, moderately sorted sandstone caps the outcrop. The exposed thickness is approximately 30 m.

PROTEROZOIC ROCKS

p€u **Proterozoic rocks**—igneous and metamorphic rocks ranging from 1.7 to 1.4 Ga (only on the cross sections).

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