# APPENDIX 2. SUMMARY OF ROCK UNITS THAT UNDERLIE THE MOGOLLON-DATIL VOLCANIC FIELD (PROTEROZOIC, PALEOZOIC, MESOZOIC, AND EARLY CENOZOIC ERAS)

## Crystalline basement

Rocks that form most of the Earth's crust – such as granite, gneiss, and schist – are commonly collectively referred to as "crystalline basement." Crystalline basement generally underlies a "skim" of sedimentary rocks or lavas that could be as thin as 1–10 ft or as thick as a ~30,000 ft. In the study area, the "skim" of sedimentary rocks and lavas is 11,500–13,000 ft thick and is penetrated by the Sun No. 1 well. This important well is located in the McClure Hills southeast of Datil (Figs. 6, 11). There, the crystalline basement is described as granitic gneiss (New Mexico Bureau of Geology and Mineral Resources (NMBGMR) Subsurface Library).

## Paleozoic sedimentary rocks

Except in the Sierra Cuchillo (mountain range located immediately south-southeast of the studied Winston graben), Paleozoic sedimentary rocks in the study area are 320 to 280 million years old and include rocks of the Pennsylvanian System in addition to overlying Permian strata: Abo, Yeso, Glorieta and San Andres formations. Paleozoic rocks are generally buried by younger strata but are exposed at two localities. One locality is found at the eastern end of Horse Mountain on the flank of the West San Agustin Basin (Fig. 1; Lucas and Kues, 1994). Other exposures of Paleozoic strata are found at the extreme south end of the Upper Alamosa basin in the northern Sierra Cuchillo, where 3,900–4,300 ft of strata dominated by limestones and dolomites have been measured and described (Jahns et al., 1978). Only the upper 2,460–2,620 ft of the section (Pennsylvanian and Permian strata) extends north of the upper Alamosa basin. Below, we summarize the Paleozoic strata from oldest to youngest. Based on outcrops, most groundwater flow in Paleozoic strata will likely be via fractures, although dissolution pathways (such as caves) are possible in Paleozoic limestones.

Older Paleozoic strata exposed only in the northern Sierra Cuchillo include the sandstone-dominated Bliss Formation overlain by several units dominated by limestone and dolomite, with subordinate shale and siltstone (Fig. A2–01). These carbonate-dominated units include the El Paso Group, Montoya Formation, Fusselman Dolomite, Oñate Formation, Percha Shale, Lake Valley Formation, and the Kelley Limestone. The collective thickness of the pre-Pennsylvanian units is ~600 ft. Many individual units are <50 ft thick, particularly the Devonian and Mississippian strata. See Jahns et al. (1978) for complete descriptions of these pre-Pennsylvanian strata.

Pennsylvanian and Permian strata extend across the entire study area and consist of the following formations (listed in ascending order): Sandia, Gray Mesa, Bar B, Bursum, Abo, Yeso, Glorieta, and San Andres formations (listed from oldest to youngest) (Fig. A2–01). Rocks of the Pennsylvanian System are dominated by limestone with variable proportions of shale and lesser sandstone and conglomerate. Pennsylvanian strata include the Sandia Formation, Gray Mesa Formation, Bar B Formation, and the Bursum Formation (oldest to youngest). The Sandia Formation, correlative to the Red House Formation in the Truth or Consequences area,

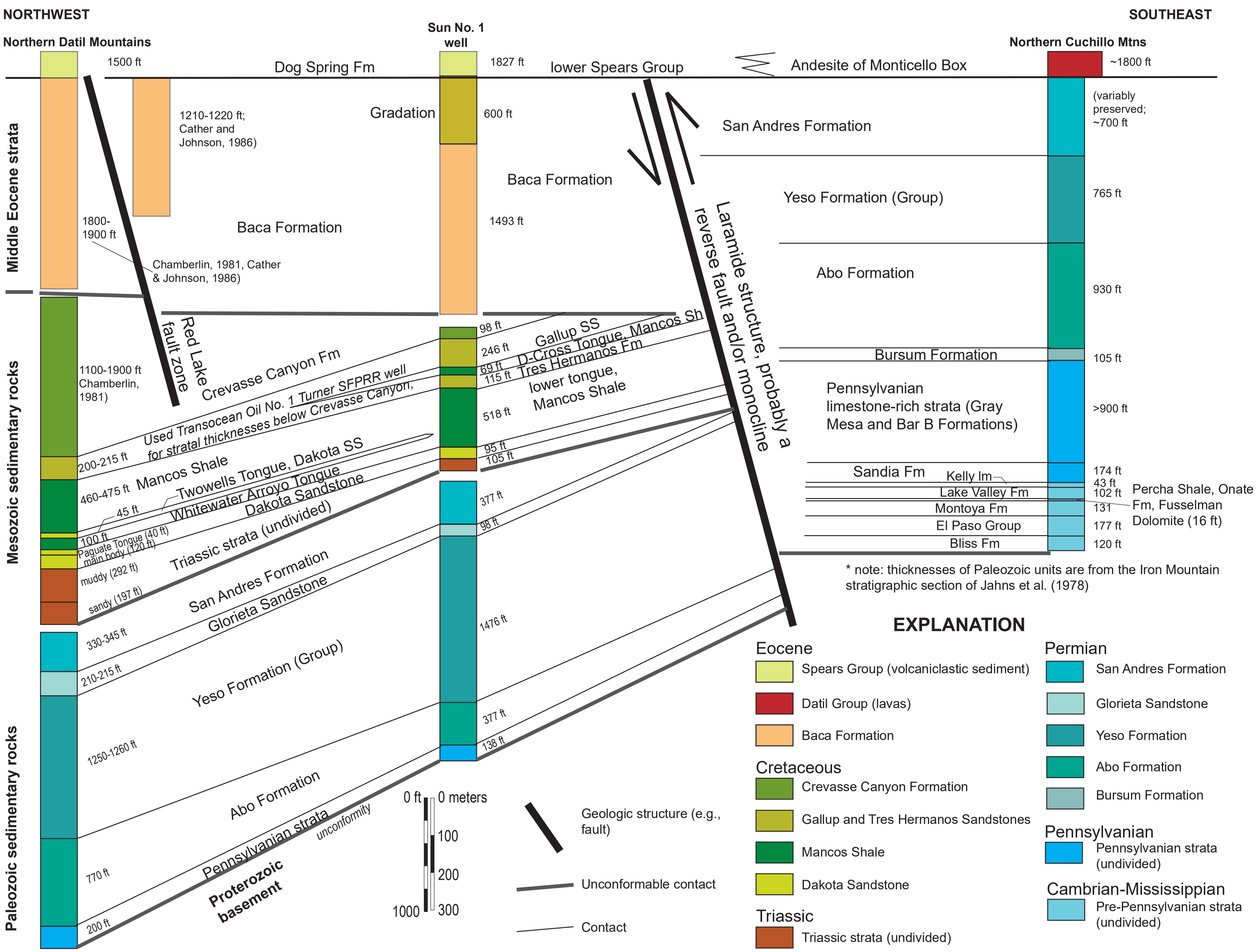


**Figure 1.** Figure A2-01. Stratigraphic correlation and thicknesses of rocks that underlie the Mogollon-Datil volcanic field. Stratigraphic columns are arranged from northwest (left) to southeast (right). The stratigraphy of the left column is from data in the Transocean Oil No. 1 Turner SFPRR well, with strata above the Gallup being from Chamberlin (1981) and Cather and Johnson (1986). The next column to the right is from the Sun No. 1 well. The pre-volcanic stratigraphy in the northern Cuchillo Mountains (right column) is from Jahns et al. (1978). Data associated with the two aforementioned wells are archived in the Subsurface Library at the New Mexico Bureau of Geology and Mineral Resources.

is composed of siltstone and silty sandstone that is interbedded with limestone (Jahns et al., 1978). Limestone-dominated strata above the Red House Formation correlates with the Nakaye (Gray Mesa Fm. *sensu* Lucas et al., 2012b) and Bar B Formations in the Truth and Consequences area. These two units consist of very thickly bedded, gray limestone with numerous shaly partings (Jahns et al., 1978). A 105 ft-thick transitional unit above the Bar B formation contains multi-colored beds (including reddish-brown and maroon) of siltstone, mudstone, and sandstone; these clastic beds are interbedded with limestone and conglomerate (Jahns et al., 1978). We correlate this transitional unit to the Bursum Formation. The thickness of the Pennsylvanian strata is quite variable, ranging from 3,100–3,200 ft east of Monticello (Koning et al., 2014) to 138 ft in the Sun No. 1 well. This thickness variability is likely a reflection of Ancestral Rocky Mountain tectonism, which occurred ~300–315 Ma in the general Socorro area (Kues and Giles, 2004, fig. 3).

Overlying the Pennsylvanian strata is a reddish, clastic interval that includes the Abo and Yeso formations (Fig. A2-01). This stratigraphic package thickens to the north-northwest, from 2,400 to 2,800 ft. The Abo Formation ranges from 380 to 930 ft in thickness and consists of red, maroon, or reddish brown siltstone, shale, and fine sandstone (Sun No. 1 well; NMBGMR Subsurface Library). To the southeast, in the Sierra Cuchillo, there are a few thin beds and lenses of limestone and limestone-pebble conglomerate near the base (Jahns et al., 1978) that likely correlate to the Bursum Formation. There is comparably less shale and more gray to light red siltstone-sandstone (very fine- to coarse-grained, mostly very fine- to medium-grained) in the Yeso Formation (Sun No. 1 well, NMBGMR Subsurface Library; Lucas and Kues, 1994), which ranges from 765 to 1,476 ft in thickness (thickening to the north). The Yeso Formation (or Group, sensu Lucas et al., 2005) also contains minor dolomite and limestone interbeds (Sun No. 1 well, NMBGMR Subsurface Library; Lucas and Kues, 1994). To the southeast, in the northern Sierra Cuchillo, there are more limestone interbeds and the siltstone-sandstone beds are yellowish, greenish, or reddish-brown (Jahns, 1955; Jahns et al., 1978; Maldonaldo, 2012). The Glorieta Sandstone consists of fine- to medium-grained quartz arenites that display abundant crossbeds; its thickness ranges from 100 to 200 ft, with an apparent eastward-thickening trend between Horse Mountain and the Sun No. 1 well (Sun No. 1 well; Lucas and Kues, 1994). The Glorieta Sandstone has not been noted in the northern Sierra Cuchillo Mountains (Jahns, 1955; Jahns et al., 1978; Maldonado, 2012). The San Andres Formation is mostly 330–380 ft thick near the Plains of San Agustin, where it is composed of light brownish gray to pinkish gray micritic limestone and dolomites (Lucas and Kues, 1994). To the southeast, in the northern Sierra Cuchillo, there are minor (~25%) interbeds of reddish to yellowish siltstone and sandstone in the San Andres Formation (Jahns, 1955; Jahns et al., 1978; Maldonado, 2012).

## Mesozoic sedimentary rocks

Sandstone, siltstone, and mudstone strata of Mesozoic age underlie the Datil and Gallinas Mountains (Fig. A2–01). These strata likely extend under the intervening northern East San Agustin basin as well as the northeastern West San Agustin basin (the latter based on the Sun No. 1 well records). A thinning of the Mesozoic package, and progressive removal of younger Mesozoic strata, is interpreted to occur southwards across buried Laramide structures in the West and East San Agustin Plains. For example, the Cretaceous Crevasse Canyon Formation is thinner at the Sun No. 1 well than in the northern Datil Mountains (Fig. A2-01). Also, interpretation of a north-south seismic line west of Datil suggests a rise in the basement reflector across a west-northwest-trending fault zone near Horse Mountain (Armstrong and Chamberlin, 1994). There are probably several other northwest- to northeast-trending Laramide structures buried under the West and East San Agustin Plains, which together resulted in Laramide net uplift under what is now the northern Mogollon Plateau. Evidence for this uplift is seen in the gravel compositions of the syn-late Laramide Baca Formation, which mostly consist of clasts consistent with a Paleozoic and Proterozoic basement provenance (see below). Also, in the lower Spears Group are large extant blocks of Paleozoic limestone, but neither blocks nor clasts of Mesozoic sediments have been observed (Harrison, 1980; Brouillard, 1984; Cather and Chapin, 1989; Cikoski et al., 2012).

Mesozoic rocks include undivided Triassic strata, Dakota Sandstone, Mancos Shale, Gallup Sandstone, and the Crevasse Canyon Formation (Fig. A2–01). Except for the Crevasse Canyon Formation, thicknesses and descriptions below are from Chamberlin et al. (1994b) and unpublished records of the Sun No. 1 well (NMBGMR Subsurface Library); the latter do not include thicknesses of igneous intrusions. Triassic strata are reddish and composed mainly of siltstone and silty mudstone, with subordinate very fine- to fine-grained, light gray sandstones. These strata are fluviatile, fluvial-lacustrine, and paludal (Stewart et al., 1972; Blakely and Gubitosa, 1983; Lucas and Hayden, 1989; Heckert and Lucas, 1994; Riggs et al., 1996). Inspection of geophysical logs of the TransOcean No. 1 Turner SFPRR well, located northwest of the study area, indicates that Triassic strata can be subdivided into an upper, muddier part (292 ft thick) and a lower part dominated by sandstone and siltstone (197 ft thick). The upper part likely correlates to the Bluewater Creek, Petrified Forest, and Owl Rock formations; the lower part may correlate to the Moenkopi and Shinarump formations (we make these correlations using lithologic descriptions and the stratigraphic schemes of Lucas and Hayden, 1989; Lucas and Heckert, 1994; Heckert and Lucas, 2003; Lucas, 2020). Triassic strata thicken notably northward, from 105 ft in the Sun No. 1 well to 489 ft at the Transocean Oil No. 1 Turner SFPRR well.

The Dakota Sandstone consists mainly of quartz-rich sandstone interbedded with subordinate shale and siltstone. Like the undivided Triassic unit, the main body of the Dakota Sandstone thickens northward from the Sun No. 1 well to the northern Datil Mountains, from 95 to 120 ft (Fig A2–01). In the Sun No. 1 well, the lower 30 ft of this unit consists of fine to very coarse sand, but in the upper 65 ft the sand is very fine to fine grained and interbedded with shale and siltstone. In the northern Datil Mountains, the 120 ft-thick main body of the Dakota Sandstone consists of a lower sandstone and shale unit (30–70 ft thick, likely correlative to the lower Oak Canyon Member), a middle carbonaceous shale unit with very minor coal (10–50 ft thick, likely correlative to the upper Oak Canyon Member), and an upper, fine- to medium-grained sandstone unit that is commonly up to 40 ft thick and correlative to the Cubero Sandstone Member (descriptions are from Chamberlin et al., 1994b, correlations are by Dan Koning). The Cubero Sandstone represents marine shoreface deposition, whereas the Oak Canyon Member strata are a mix of fluvial, deltaic, and shoreface deposits (Owen and Sparks, 1989; Owen and Owen, 2003).

Above the main Dakota Sandstone body in the northern Datil Mountains, interbedded in the lower Mancos Shale, are the Paguate Tongue (40 ft thick) and the younger Twowells Tongue (45 ft thick), whose thicknesses are from well log interpretations of the Transocean Oil No. 1 Turner SFPRR well (NMBGMR Subsurface Library). In west-central New Mexico, these two tongues consist of very fine- to fine-grained sand that coarsen upward (Owen and Sparks, 1989; Chamberlin et al., 1994b). The two tongues are interpreted as regressive shoreface marine sands, although east of Gallup the Paguate includes coastal swamps and distributary channel fills (Owen and Sparks, 1989; Owen and Owen, 2003).

Above the Dakota Sandstone lies a 460–520 ft thick interval of Mancos Shale overlain by the Tres Hermanos Formation (Fig. A2-01). The Mancos Shale is mostly shale to silty shale and medium-gray (Chamberlin et al., 1994b), with beds of limestone and calcarenite located 100–115 ft above the Twowells tongue of the Dakota Sandstone (based on lithologic and geophysical logs of the Sun No. 1 and the Transocean Oil No. 1 Turner SFPRR wells, respectively; NMBGMR Subsurface Library). In the Sun No. 1 well, there are 3-5% interbeds of very fine- to fine-grained, quartzose sandstone. The Mancos Shale was deposited in an offshore marine environment (Pike, 1947).

The Tres Hermanos Formation is composed of very fine- to medium-grained, quartzose sandstone that generally coarsens-upwards (Chamberlin et al., 1994b). It is ~115 ft thick in the Sun No. 1 well but thins to 45 ft near Quemado (Chamberlin et al., 1994b). Using the terminology and interpretations of Hook et al. (1983), the Tres Hermanos Formation consists of a lower regressive shoreface complex (Atarque Sandstone Member) and possibly a marginal marine-nonmarine, shale-bearing upper part ("Carthage Member" of Hook et al., 1983, renamed "Campana Member" by Lucas et al., 2019), although shales are not noted in the Sun No. 1 well lithologic logs. Above the Tres Hermanos Formation lies another tongue of Mancos Shale (D Cross Tongue) that is 69 ft thick in the Sun No. 1 well.

The Gallup Sandstone consists of interbedded shale-siltstone and very fine- to medium-grained sandstone, intervals of the latter seldom exceed 16 ft. The sandstone was deposited in a nearshore environment, whereas the shale-siltstone are typically associated with offshore deposition (Molenaar, 1983). This unit is 246 ft thick in the Sun No. 1 well, but interpretation of its true thickness in the Transocean Oil No. 1 Turner SFPRR well is hindered by the presence of an intrusive body (probably a sill).

The Crevasse Canyon Formation consists of interbedded channel-fill sandstones and floodplain deposits. Channel-fills are composed of yellowish brown to yellowish gray, fine- to medium-grained feldspathic sandstones (Chamberlin et al., 1994b). Floodplain deposits include yellowish brown shales, dark gray carbonaceous shales, gray siltstones, and local thin coal seams (Chamberlin et al., 1994b). Its base is transitional with nearshore sediments of the Gallup Sandstone. The Crevasse Canyon Formation is interpreted as a fluvial deposit, with some of the mudstones being paludal (Chamberlin, 1981). On top of the Crevasse Canyon Formation lies a 25–150 ft-thick strongly oxidized zone, where mudstones are mottled and there are local spherical concretions of hematite-cemented sandstone (Chamberlin, 1981, 1989). This zone is interpreted to be a subsolum ("C" horizon) of a lateritic paleosol (Chamberlin, 1981, 1989). The Crevasse Canyon Formation is only about 98 ft thick in the Sun No. 1 well, but thickens northward to 1100-1900 ft in the northern Datil Mountains.

## Baca Formation (Early Cenozoic)

The Baca Formation consists predominately of reddish mudstones and red to light gray sandstone deposited in a closed basin in the late-early to middle Eocene. It is found only in the northern part of the study area, where it is 750–1,900 ft thick (Fig. A2–01; Chamberlin, 1981; Cather, 1980; Cather and Johnson, 1984). Baca Formation sandstones are moderately to well cemented by calcite and lesser silica, and are inferred to make better aquifers than the more strongly cemented sediments of the overlying Spears Group (Chamberlin et al., 1994b; S. Cather, personal commun., 2014).

The Baca Formation outcrops on the north end of the Datil and Gallinas Mountains. It was encountered in the Sun No. 1 well in the McLure hills (Figs. A2–01, 6 and 11 of main manuscript), where it is 1,493 ft thick. In the Sun No. 1 well, this unit has a triparte, coarsening upward character. The lower 705 ft is largely mudstone with a few thin beds of arkosic, fine to coarse sandstone. In the middle 479 ft, sandstone is more abundant but still subordinate to mudstone and siltstone; the sand is mostly very fine- to fine-grained (locally medium to very coarse), and composed of quartz, feldspar, and chert. In the upper 308 ft, sandstone is subequal to mudstone-siltstone and composed of quartz and quartzite grains that are commonly frosted (description from unpublished records for the Sun No. 1 well; NMBGMR Subsurface Library). The sedimentology and stratigraphy of the Baca Formation was studied by Wipolt et al. (1946), Potter (1970), Snyder (1971), Johnson (1978), Schrodt (1980), and Cather (1980, 1982, 1983) – with an excellent summary given by Cather and Johnson (1984, 1986).

The Baca Formation ranges in age from 51 to 38 Ma, disconformably overlies Cretaceous strata (mostly Crevasse Canyon Formation), and is gradationally overlain by the Spears Group, with the upper contact gradational over 15–30 ft (although in the Sun No. 1 well the gradational zone may be as great as 600 ft; based on Dan Koning's inspection of unpublished records for the Sun No. 1 well; NMBGMR Subsurface Library). The minimum (youngest) age of the Baca Formation is provided by volcanic clasts in the lower part of the overlying Spears Group, which have returned K/Ar and $^{40}Ar/^{39}Ar$ ages on biotite ranging from 37.1 ± 1.5 Ma to 38.6 ± 1.5 Ma (Burke et al., 1963; Bornhorst et al., 1982; Cather, 1990; Cather et al., 1987; Cather and Johnson, 1984). However, a 40Ar/39Ar age of 36.94 ± 0.07 Ma from a single sanidine crystal is interpreted to be more representative of the age of the lower Spears Group, and provides a minimum age constraint for the Baca Formation (McIntosh and Chamberlin, 1994). Paleomagnetic reversal stratigraphy indicate that the upper part of the Baca Formation is 38.2–38.3 Ma (Prothero et al., 2004). Vertebrate fossils collected by Snyder (1970), Cather (1980), Schrodt (1980), and Schiebout and Schrodt (1981) are interpreted by later workers (namely Lucas (1983, 2015) and Lucas and Williamson, 1993) to belong to the Bridgerian? to late Duchesnean North American Land-Mammal "ages," which range from 46.2–37.2 Ma (Fossilworks, 2014). Synthesizing these data, we consider that the likely age of the Baca-Spears contact is 38 Ma. The lowest part of the unit may possibly be as old as 50.3 Ma (Lucas and Williamson, 1993), which is the maximum age of the Bridgerian North American Land Mammal "stage" (Fossilworks, 2014).

The closed basin associated with Baca deposition consisted mostly of braided alluvial plain river (fluvial) systems draining towards a lake 10–20 mi northwest of Magdalena (Cather, 1982, 1983; Cather and Johnson, 1984, fig. 25). The basin extent was highly asymmetric and extended from north of Magdalena westward past Show Low in Arizona. Laramide highlands surrounded the basin on all sides. Of these, the Mogollon Highlands in eastern Arizona (near what is now the town of Morenci) appeared to be the highest and largest, since it contributed the most sediment to the basin (Cather and Johnson, 1984). A number of depositional system tracts have been recognized in this basin, which we summarize below.

Paleo-lake sediment (10–20 mi northwest of Magdalena) consists of roughly subequal sandstone and mudstone, with the sandstone attributed to deltaic deposition. The deltaic sediment exhibits cyclical, upward coarsening trends on the scale of ~15 ft. Inward of the deltas (towards the center of the lake), silt and clay settled out of suspension or via turbidity currents in standing water, but were then commonly homogenized and bioturbated by burrowing organisms.

The braided alluvial plain can be subdivided into a proximal, medial, and distal fan facies (Cather and Johnson, 1984). The proximal fan facies is dominated by conglomerate that is interbedded with lenses (≤3.5 ft thick) of very coarse sandstone. Gravel include pebbles through boulders that are clast supported, crudely imbricated, and have a matrix of sand. In the medial fan facies, conglomerate is subequal or slightly less than sandstone. The conglomerates occur as lens- or channel-shaped units as much as 15 ft thick and 100 ft wide. Sandstone is fine- to very coarse-grained and occur as laterally extensive, sheet-like deposits and in channel-shaped units as wide as 160 ft. The distal fan facies is inferred to occupy a 5–10 mi-wide band surrounding the central lake (Cather and Johnson, 1984). It consists of fine- to very coarse-grained sandstone with subordinate conglomerate, mudstone, and claystone. Sandstone occurs as sheet-like bodies, and the mudstone and claystone occur as thin, laterally continuous beds.