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GEOLOGY OF NORTHEASTERN NEW MEXICO, UNION AND COLFAX COUNTIES, NEW MEXICO: A GEOLOGIC SUMMARY

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Abstract — The geology of northeastern New Mexico encompasses a range of Mesozoic and Cenozoic sedimentary rocks overlying Precambrian basement. The region has also been the site of abundant late Cenozoic eruptions represented by the compositionally diverse range of volcanic rocks of the Raton-Clayton volcanic field. Volumetrically minor mid-Tertiary sills and dikes are also exposed throughout northeastern New Mexico. Broad regional upwarping of the area has produced generally east-west arches that overprint much of the overlying stratigraphy. Overall, the region presents a range of rock types, rock ages, and structural and geomorphologic features that reflect the diversity of regional geology and offers a great location for the 70th New Mexico Geological Society Fall Field Conference.

INTRODUCTION

The geology of northeastern New Mexico is largely characterized by Triassic to Pliocene sedimentary strata that are commonly intruded and/or covered by upper Oligocene to Pleistocene volcanic rocks. The area is within the tectonically stable Great Plains province, a region characterized by thick crust and mantle lithosphere. The Raton-Clayton volcanic field of northeastern New Mexico is the northeastern-most expression of the Jemez lineament, a series of volcanic fields that extends from Springerville, Arizona to northeastern New Mexico. Overall, a southwest to northeast structural fabric characterizes the upper crust in northeastern New Mexico with many volcanic vents aligned along faults related to these features. Thick sedimentary stratigraphic sequences underlie most of the region with continuous exposures present in the valley of the Dry Cimarron River along the New Mexico/Colorado border and along mesa fronts in Colfax County. These thick sequences unconformably overlie Precambrian granitic and metamorphic rocks at depth. The land surface in this area is dominated by high mesas and low gently sloping valleys that are interrupted by smaller and lower elevation basalt-capped mesas, small intermediate to mafic volcanic cones, and the much larger edifice of the ~2-3 Ma Sierra Grande composite volcano. Human activities that impact the geomorphology and hydrology in the area include the many wagon ruts of the Santa Fe Trail (including the Cimarron Cut-off), the railroad system, open-range cattle ranching and some center-pivot irrigation farming.

REGIONAL SETTING

Northeastern New Mexico is located near the intersection of the Rocky Mountains to the west and the High Plains to the east (Fig. 1). The western edge of the area is defined by the high relief of the Sangre de Cristo uplift, which transitions eastward into the Raton Basin, a deep synclinal basin with a north-south trending axis that preserves a thick sequence of several thousand feet of Paleozoic to early Cenozoic sedimentary rocks. The sediments of the Raton Basin onlap onto the Sierra Grande Arch and Bravo Dome, Precambrian-cored uplifts in the subsurface related to the Ancestral Rocky Mountains (Ewing, *this volume*). Eastward of the Sierra Grande Arch, sedimentary sequences are preserved in the Dalhart Basin on the margin of the craton.

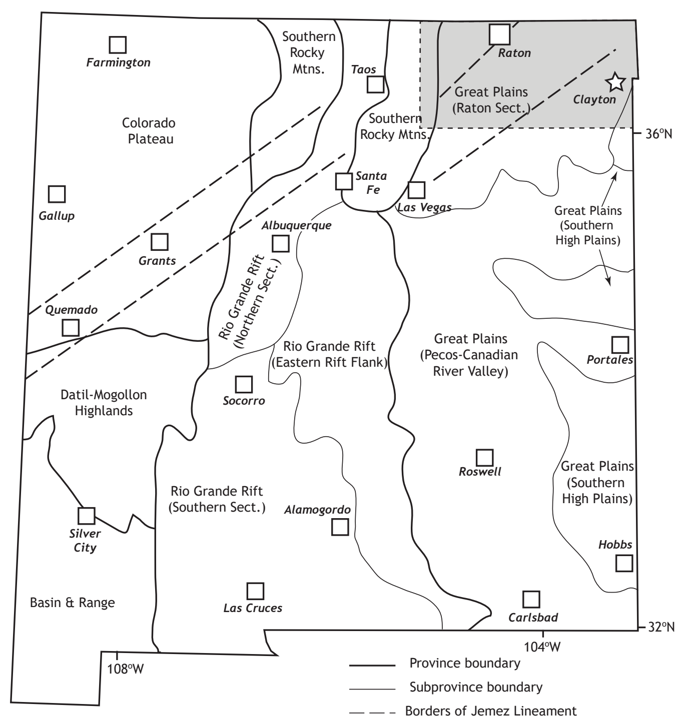


FIGURE 1. Map showing physiographic provinces of New Mexico from Pazzaglia and Hawley (2004) with the location Union and Colfax counties in the gray dashed box.

The Sangre de Cristo Mountains are a Laramide uplift bounded on the western margin by the Rio Grande Rift. The eastern margin is defined by Laramide reverse and thrust faults adjacent to the Raton Basin that accommodate up to nearly 4,700 m (3 miles) of structural relief (Northrop et al., 1946; Woodward, 1987). The easternmost component of the Sangre de Cristo uplift, the Cimarron Range, is bounded by the Fowler Pass fault, a high-angle reverse fault on the north and east edges of the range. Cenozoic igneous intrusions emplaced along this fault are now preserved as localized silicic igneous rock outcrops.

The Raton Basin, which includes the Las Vegas sub-basin, is approximately 300 km (185 miles) north-south and 100 km (60 miles) east-west. A strongly asymmetric basin, the western limb is characterized by steeply dipping to locally overturned beds, whereas the eastern limb is more gently dipping and merges to the east with the Sierra Grande and Apishapa arches. The Raton Basin includes several thousand meters of upper Paleozoic through Tertiary sedimentary rocks that include deposits that are synorogenic with Laramide deformation (Baltz, 1965; Johnson and Wood, 1956; Woodward, 1987). The Raton Basin is partially separated from the Las Vegas sub-basin by the Cimarron Arch (not to be confused with the Cimarron Range to the north; Woodward, 1983, 1987). A number of smaller anticlines and domes occur in or along the margins of the Raton Basin; some were developed by shallow intrusion of igneous rocks (e.g., the Turkey Mountains near Wagon Mound), whereas others were formed by compression along the western margin of the basin.

The Sierra Grande Arch and Bravo Dome are considered Ancestral Rocky Mountain uplifts that developed during the Pennsylvanian. As these areas were uplifted along bounding faults, overlying Paleozoic strata were stripped off exposing Precambrian basement (Baltz, 1965; Broadhead and King, 1988; Broadhead, 1990; Baltz and Myers, 1999; Broadhead, *this volume*). Sediments eroded from these newly-formed uplifts were deposited in adjacent basins from the Late Pennsylvanian through the Early Permian. The Sierra Grande Arch trends northeast-southwest and separates the Raton Basin to the west from the Dalhart Basin to the east. It is approximately 250 km (155 miles) northeast-southwest and 40 to 110 km (25 to 65 miles) northwest-southeast, depending on the definition of the margins of the adjacent basins (Woodward, 1987). The Bravo Dome is a southeast-plunging anticline that extends to the southeast from the Sierra Grande Arch (Broadhead, *this volume*). Folds and domes occur along the margins of the Sierra Grande Arch. The domes are probably laccolithic in origin due to the abundance of Tertiary igneous rocks in the area (Woodward, 1987). Bates (1942) also identified three anticlines along the greater Clapham anticline south of Clayton, and Baldwin and Muehlberger (1959) identified the Guy monocline in the Dry Cimarron. The Clapham anticline may also include a component of paleotopography developed on the top of the Morrison Formation.

SEDIMENTARY BEDROCK GEOLOGY

The sedimentary sequence visible in Colfax and Union Counties consists primarily of the Upper Triassic Dockum Group through the Miocene-Pliocene Ogallala Formation (Fig. 2). These units overlie Precambrian basement composed of granitic rocks or thin sequences of Paleozoic sedimentary rocks in the subsurface.

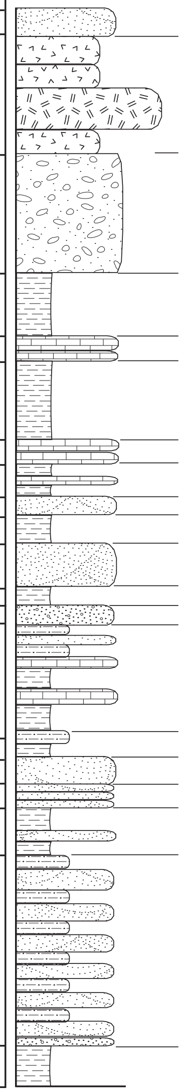
Triassic System

The oldest strata exposed in Union County, the Triassic Dockum Group, are found in the Dry Cimarron Valley and its tributaries. The "redbeds" were first described in the early 1900s (e.g., Lee, 1902; Rothrock, 1925; Darton, 1928, among others). Baldwin and Muehlberger (1959) were the last to spend significant time mapping the strata in the region and their work was built upon by Lucas et al. (1987), who described additional stratigraphic sections of these units. Beginning in 1987, these strata were referred to the Chinle Group (Lucas et al., 1987), but Cather et al. (2013) designated Upper Triassic strata east of the Rio Grande rift as belonging to the Dockum Group and the nomenclature of Cather et al. (2013) is followed here.

Dockum Group units include (in ascending age order) the Baldy Hill Formation, Travesser Formation, Sloan Canyon Formation locally, and the Sheep Pen Sandstone (Baldwin and Muehlberger, 1959; Lucas et al., 1987). Taken together, this sequence represents aggradational fan, fluvial, and lacustrine deposition in a broad, low-relief basin that includes portions of West Texas, southern Colorado, New Mexico, Arizona, Utah and Nevada. The Baldy Hill Formation is the oldest unit exposed in Union County and consists of dark purple, reddish-brown and greenish-gray silty mudstone with sandy mudstone and very fine-grained sandstone that is more than 35 m (>115 feet) thick. The base of the unit is not exposed in the area. The top of the unit is marked by a laterally persistent series of grayish-purple intraformational conglomerate beds that Lucas et al. (1987) termed the "Cobert Canyon Sandstone Bed". Above the Cobert Canyon Sandstone is the Travesser Formation, which includes brick red to reddish brown siltstone and fine-grained sandstone interbeds. The sandstone units are up to 6 m (20 feet) thick, range from massive to thin-bedded or ripple-cross laminated, and locally include lenses of intraformational conglomerate. The Sloan Canyon Formation was previously mistaken to be part of the Morrison Formation due to its variegated mudstone beds (Rothrock, 1925; Darton, 1928). It consists of 38 to 46 m (125 to 150 feet) of variegated purple, green, and reddish-brown mudstone with siltstone and marl horizons. The Sheep Pen Sandstone comprises over 18 m (60 feet) of tan, thin-bedded to massive sandstone. Baldwin and Muehlberger (1959) suggested a slight angular discordance between the Sheep Pen Sandstone and the underlying Sloan Canyon Formation in one outcrop.

Broad, gentle folding of the Dockum Group has resulted in variable thickness of the Sloan Canyon Formation, Sheep Pen Sandstone, and overlying Jurassic Exeter Sandstone. Along anticline hinges, the Sloan Canyon Formation and Sheep Pen Sandstone have been eroded and the overlying Exeter Sandstone is thin to nonexistent (Baldwin and Muehlberger, 1959). Syncline hinges preserve the thickest sequences of Sloan Canyon Formation, Sheep Pen Sandstone and Exeter Sandstone.

Geologic Age	Stratigraphic Unit		General Rock Type(s)	Avg. Thickness
Quaternary			Eolian sand sheets, dune and alluvial deposits.	~0-30 m
Quaternary / Miocene-Pliocene	Raton-Clayton-Capulin volcanics		Dark gray to black basalts, cinder cones and fissure vents ranging in age from ~ 36 ka - ~ 9 Ma. Incl. Sierra Grande: med. gray andesite, ~2.6-3.8 Ma.	
Miocene-Pliocene	Ogallala Fm.		Reddish-brown to tan coarse-grained sand with local lenses of pebble to cobble conglomerate. Heavily bioturbated. Locally capped by well-developed calcrete.	0 - 200 m
Cretaceous	Smoky Hill Marl (Niobrara Fm.)		Dark gray silty to sandy shale with thin beds of limestone and marl.	305 m
Cretaceous	Ft. Hays Ls.		Pale gray medium bedded limestone	15 m
Cretaceous	Carlile Shale		Dark gray shale with thin limestone beds in upper section.	61 m
Cretaceous	Greenhorn Ls.		Gray shale and pale gray medium-bedded micrite beds.	9 m
Cretaceous	Graneros Shale		Medium gray shale with thin fossiliferous limestone beds.	38 m
Cretaceous	Dakota Group	Romeroville Ss.	Yellowish-gray medium-grained, locally pebbly sandstone.	0-8 m
Cretaceous	Dakota Group	Pajarito Shale	Medium gray shale.	10-20 m
Cretaceous	Dakota Group	Mesa Rica Ss.	Brownish-yellow persistent medium grained, cross-bedded sandstone.	33 m
Cretaceous	Glencairn Fm.		Gray to dark gray shale, siltstone and sandstone.	22 m
Cretaceous	Lytle Ss.		Light gray conglomeratic cross-bedded sandstone.	10-20 m
Jurassic	Morrison Fm.		Gray-green and red mudstone with locally thick medium to coarse-grained sandstone and thin micrite beds.	52-168 m
Jurassic	Bell Ranch Fm.		Dark brown mudstone with nodules of alabaster.	0-8 m
Jurassic	Exeter Sandst.		White to pale pink cross-bedded sandstone.	0-24 m
Late Triassic	Dockum Group	Sheep Pen Ss.	Light-brown, thin-bedded sandstone.	0-33 m
Late Triassic	Dockum Group	Sloan Canyon Fm.	Red and pale gray-green mudstone with lenses of medium-grained sandstone.	0-46 m
Late Triassic	Dockum Group	Travesser Fm.	Reddish-brown siltstone and sandstone with local intraformational conglomerate lenses.	75-168 m
Late Triassic	Dockum Group	Baldy Hill Fm.	Purple, red and green mottled mudstone with lenses of coarse-grained sandstone. Base not exposed.	> 30 m



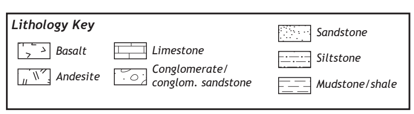


FIGURE 2. Schematic stratigraphic column showing Mesozoic and Cenozoic sedimentary units and Cenozoic volcanic units in Union and Colfax County.

In addition to the folding of the Dockum Group, numerous clastic plugs or injectites litter the valley floor, beginning just east of the junction of Lake Highway and Dry Cimarron Highway (McLemore, *this volume*, includes a detailed discussion of the injectites).

Jurassic System

There is a hiatus at the top of the Triassic rock sequence that represents the Early Jurassic. Thus, rocks of Middle and Late Jurassic age rest directly on the Dockum Group and include the Exeter Sandstone, Bell Ranch Formation, and Morrison Formation. The Exeter Sandstone, a relatively thick sequence of pale red to white quartz sandstone that either lacks features or contains large crossbeds (Lee, 1902; Baldwin and Muehlberger, 1959; Mankin, 1972), is presumed to be the easternmost extent of the large-scale Entrada dune field that covered much of the Four Corners region. There is currently little age control on the Exeter Sandstone. Correlation of the Exeter Sandstone was first suggested by Heaton (1939), who demonstrated that the Entrada Sandstone in Utah was correlative to outcrops in the Front Range of Colorado. Baldwin and Muehlberger (1959) followed his interpretation that the Exeter Sandstone is equivalent to the Entrada Sandstone. Exeter Sandstone thickness varies significantly from not present to 25 m (80 feet) where it infills synclinal valleys in the underlying Dockum Group.

Above the cliff-forming Exeter Sandstone are outcrops of the Bell Ranch and Morrison Formations. The Bell Ranch Formation is brownish-red mudstone with nodules and zones of gypsum considered to be the lower "brown-silt member" of the Morrison Formation by Baldwin and Muehlberger (1959). Conrad et al. (1987) designated the "brown-silt member" as equivalent to the Bell Ranch Formation (Lucas et al., 1985) to the south in Quay County. At the type section of the Bell Ranch Formation, the unit is described as "…cyclically bedded fine- to coarse-grained sandstone and siltstone" and several of the sandstone beds contain significant gypsum contents (Lucas et al., 1985). In the Dry Cimarron, this unit is darker in color, does not contain cyclical bedding and has significant gypsum contents throughout its thickness, suggesting a change in facies within the unit from south to north. The thickness of this unit varies considerably from zero to up to 23 m (75 feet).

The Morrison Formation consists of two facies aside from the "brown-silt member" of Baldwin and Muehlberger (1959): a lower silty mudstone, sandstone, and limestone sequence and an upper variegated mudstone and sandstone sequence (Baldwin and Muehlberger, 1959; Mankin, 1972). The lower facies includes multiple thin beds of micritic limestone interpreted as lacustrine in origin. In the upper portion of the Morrison, the proportion of mudstone and sandstone can vary significantly from outcrops dominated by mudstone to outcrops consisting almost entirely of white fine- to medium-grained sandstone. Near the base of the Morrison Formation is a unit referred to as the "agate bed," which consists of stringers of red chert or jasper suggested to represent a poorly developed silcrete.

Cretaceous System

The Morrison Formation is overlain by strata that are Cretaceous in age and include the Lytle Sandstone, the Glencairn Formation, the Dakota Group, the Graneros Shale, and the Greenhorn Limestone in Union County. In Colfax County, the Raton Basin preserves the Niobrara Formation, Raton Formation and Vermejo Formation, which extend into Paleocene time. Baldwin and Muehlberger (1987) and Kues and Lucas (1987) provide an excellent review of the Cretaceous stratigraphy in the Dry Cimarron.

The lowest Cretaceous strata in the sequence are beds of the Lytle Sandstone, previously termed the Purgatoire Formation (Baldwin and Muehlberger, 1959; Kues and Lucas, 1987). It consists of a very pale pink interval of sandstone and siltstone beds that forms a prominent band low in the cliffs of the Dry Cimarron Valley (Kues and Lucas, 1987). Baldwin and Muehlberger (1959) and Mateer (1987) documented the difficulties in placing the boundary between the underlying Morrison Formation and Lytle Sandstone due to similarities between Morrison sandstone beds and Lytle Sandstone beds. Recent work by Bartnik et al. (*this volume*) utilizes detrital zircon age spectra to suggest that the Lytle Sandstone may be Jurassic in age.

Above the Lytle Sandstone are gray shales and buff-colored sandstones and siltstones that often contain abundant oysters of *Texigryphea* (Kues and Lucas, 1987). The lowest portion of the Glencairn Formation is up to three meters of sandstone designated the "Long Canyon Sandstone Bed" that is massive, laminar, and bioturbated with abundant invertebrate faunal assemblages that indicate a late Albian age (Stanton, 1905; Kues and Lucas, 1987). The unit grades upward into a dark, organic-rich mudshale, then into an upper oxidized siltstone and sandstone facies that locally contains fossil plant material (Kues and Lucas, 1987).

The Dakota Group consists of a lower thick sandstone unit, a middle shale unit, and an upper sandstone unit (Kues and Lucas, 1987). The lower sandstone is the Mesa Rica Sandstone and represents deposition in a braided river system. The shale unit, termed the Pajarito Formation, contains oyster shell fragments and was deposited under shallow-marine conditions during the late Albian. The upper sandstone is the Romeroville Sandstone and is a complex sequence of beach sands, bar deposits, and thin shales representing slightly deeper water conditions.

Above the Romeroville Sandstone is the Graneros Shale, which consists of dark gray shales and mudstones with bentonite beds as well as thin limestone beds in the middle part of the unit and is also Albian in age (Kues and Lucas, 1987). The Graneros Shale is conformable with the upper Dakota Group (Griggs, 1948; Baldwin and Muehlberger, 1959). Often these thin limestone beds contain numerous inoceramid oyster shells, rare shark teeth, and impressions of ammonoids. Siderite nodules and large concretions occur throughout the thickness of the unit. The Graneros Shale is only preserved in localized outcrops in much of Union County although thicker, better-preserved sections occur to the west into Colfax County.

The youngest Cretaceous unit preserved in Union County is the Greenhorn Limestone, a rhythmically bedded limestone and shale unit, that occurs primarily in the northwestern part of the county. Better-preserved sequences of Greenhorn Limestone occur in Colfax County where the unit can be up to 52 m (170 feet) thick. The Greenhorn Limestone is conformable with the underlying Graneros Shale and is composed of interbedded thin limestone beds and gray shale. The limestone beds are generally micritic, although many contain foraminifera fossils, are gray to black in color, and weather to a very pale gray. In contrast to limestone in the Niobrara Group, the limestone beds in the Greenhorn Limestone are all less than 30 cm thick (Griggs, 1948).

The Carlile Shale sits conformably above the Greenhorn Limestone and is upwards of 37 m (120 feet) thick, although it is frequently covered by colluvium, landslides, and thin veneers of soil. The lower Carlile Shale is moderately calcareous, dark gray shale and the upper Carlile Shale includes two distinctive zones: a lower zone of large calcareous septarian concretions and an upper zone of highly fossiliferous limestone and silty shale. Common invertebrate fossils that occur in the upper Carlile are *Ostrea*, *Scaphites warreni*, *Prionocyclus wyomingensis*, and shark teeth (Griggs, 1948).

The Niobrara Formation is conformable with the upper Carlile Shale and is approximately 290 m (950 feet) thick, making it the thickest of the Cretaceous units preserved in Colfax County. The Niobrara Formation is divided into two units: a lower interbedded shale and limestone sequence and an upper shale unit. The lower limestone-shale sequence is equivalent to the Fort Hays Member of Dane et al. (1937) and the upper sequence to the Smoky Hill Member. The Fort Hays Member includes up to 7 m (20 feet) of limestone and shale interbeds. The limestone beds are thicker than those observed in the Greenhorn Limestone, are dark gray and micritic, and weather to a yellowish-gray color. Due to the greater resistance of the thicker limestone beds, the Fort Hays Member tends to form benches and escarpments. The Smoky Hill Member, which comprises the rest of the thickness of the Niobrara Formation, is generally covered by colluvium and/or soil in most areas. Approximately 76 m (250 feet) from the base of the member, a 30 m (100 feet) thick zone of sandy, yellowish, arenaceous shale occurs that is exposed in low roadcuts throughout the central part of Colfax County. Above the sandy interval, the remainder of the Smoky Hills Member is gray shale.

The Pierre Shale overlies the Niobrara Formation and is conformable with the lower unit. It is almost entirely covered in Colfax County, but petroleum well records suggest it is nearly 503 m (1,650 feet) of noncalcareous black shale with a 15 m (50 feet) thick sandy zone at the top of the unit. The Trinidad

Sandstone lies conformably above the Niobrara Formation and interfingers with it. It is composed of approximately 30 m (100 feet) of thin-bedded to massive, light gray arkosic sandstone that represents deposition in a large delta complex with sediments redistributed into a barrier-bar system (Cather, 2004). The Trinidad Sandstone is conformably overlain by the Vermejo Formation, which consists of sandstone, shale and coal beds deposited in a coastal plain environment (Lee and Knowlton, 1917; Cather, 2004). Almost all the coal mined in Colfax County comes from coal horizons in the Vermejo Formation.

Tertiary System

The Upper Cretaceous-Paleocene Raton Formation sits unconformably above the Vermejo Formation and ranges in thickness from zero due to erosion, to upwards of 610 m (2,000 feet) to the west of Raton. It is composed of coal, carbonaceous shale, sandy shale, arkosic sandstone and basal conglomerates (Griggs, 1948; Cather, 2004). It is primarily sandy shale and sandstone that is poorly cemented. The unconformity between the underlying Vermejo Formation and Raton Formation has been interpreted to represent a hiatus in deposition between two episodes of subsidence of the Raton Basin (Cather, 2004). The Raton Formation includes the K-T Boundary, which is exposed in a local outcrop above the city of Raton and has been identified in drill holes near York Canyon (Tschudy, 1973; Pillmore et al., 1984; Shoemaker et al., 1987; Obradovich, 1993; Cather, 2004).

The Miocene-Pliocene Ogallala Formation, well known on the High Plains for its characteristics as an aquifer (Baldwin and Muehlberger, 1959), is the only part of the younger Cenozoic record preserved in this area. The Ogallala Formation is a complex unit that represents deposition in fluvial, eolian and aggradational fan systems that were carrying material from the newly uplifted Rocky Mountains. The lower Ogallala Formation usually consists of some proportion of cobble to boulder conglomerate and coarse-grained sandstone with lenses of sandy mudstone that fines upwards into medium- to coarse-grained sandstone that becomes pervasively cemented with calcite, forming the hard caliche caprock observed throughout eastern New Mexico and West Texas. Ogallala deposits primarily fill incised landscapes and are preserved as thin gravel or calcrete lenses capping local high points or as paleovalley-fill sequences in the subsurface. The uppermost deposits of this unit are capped by a series of petrocalcic paleosols, often termed The Caprock in western Texas. The top of the Ogallala is locally scoured out and filled with Quaternary stream deposits (Baldwin and Muehlberger, 1959). Subcrops of the Ogallala Formation exert a strong control on local center-pivot irrigation (see Zeigler et al., *this volume*).

REGIONAL VOLCANISM AND MAGMATISM

Volcanism in northeastern New Mexico is mainly encompassed by the Raton-Clayton and Ocate volcanic fields (Aubele and Crumpler, 2001). In Union and Colfax counties, only rocks associated with the Raton-Clayton volcanic field are present. This region is located at the northeastern end of the Jemez lineament and is also the easternmost extent of Cenozoic volcanism in North America. Late Cenozoic volcanism in this region, as well as that along the southwestern segment of the Jemez lineament and within the Rio Grande rift, is attributed to decompression melting of upwelling asthenosphere during continental extension (Baldridge, 2004). Available geochronological data does not indicate a temporal-spatial pattern along the entire length of the Jemez lineament (Chapin et al., 2004), however, vent migration patterns have been identified within individual fields of the lineament, such as those within the Raton-Clayton field (Zimmerer, *this volume*).

The Raton-Clayton volcanic field consists of over 140 vents located between Raton to the west, Clayton to the southeast, and Trinidad (Colorado) to the northwest (Aubele and Crumpler, 2001). Some of the most distal lava flows from the easternmost vents crop out in Oklahoma. In total, the field covers ~ 20,000 km^2 (7,700 square miles) making it the spatially largest volcanic field of the Jemez lineament. The oldest rocks are ~9 Ma and the youngest rocks are ~36 ka (Zimmerer, *this volume*). Raton-Clayton volcanic rocks range from silica undersaturated with compositions ranging from olivine nephelinite to basanite, to silica saturated that are typically basaltic in composition. In addition to less-evolved compositions, the region also hosts the more-evolved Red Mountain dacite exposed as vents, dikes, and plugs. Additionally, Sierra Grande, the highest peak in the region and largest edifice of the field, is composed of two-pyroxene andesite.

The oldest lavas in the region are composed of Raton-phase olivine basalt, which erupted between 9.1 and 3.6 Ma (Stroud, 1997; Nereson et al., 2013). Many Raton basalts are found capping topographic features such as mesas in the western and central portions of northeastern New Mexico, such as those between Raton and Trinidad. In some places, Raton basalts are capped by younger volcanic rocks. They are typically monotonous olivine-bearing basalts that may contain small amounts of sedimentary xenoliths and quartz xenocrysts (Stormer, 1972). They are less differentiated igneous rocks and are thought to be generated from mantle. However, the silicic xenoliths and xenocrysts suggest some crustal contamination, but detailed petrochemical evaluations of their origins have not been undertaken using modern techniques.

Included in Raton-phase volcanism, but with very different compositions, are volcanic features associated with Red Mountain dacite. Red Mountain dacite, also referred to as Red Mountain rhyodacite, is a general term used to describe vents, domes, and eroded flows present in the Raton-Clayton field that are more silicic than Raton-phase basalts (Stormer, 1972). These features post-date the beginning of Raton-phase volcanism but predate or are coeval with the next younger Clayton-phase of basaltic volcanism affecting the region. Red Mountain dacite consists of hornblende bearing andesites and dacites that commonly form the conspicuous higher peaks south of Highway 64 such as Green Mountain, Laughlin Peak, and Palo Blanco Mountain. Additional volcanic features composed of Red Mountain dacite, such as Red Mountain, are also present on mesas north of Highway 64 (e.g., Johnson Mesa).

Many Red Mountain dacite centers remain undated, but those that have yield ages from as old as 8.2 Ma (Stormer, 1972) to as young as 4.0 Ma (Aubele and Crumpler, 2001).

Following eruption of Raton-phase basalts and Red Mountain dacite, basaltic volcanism continued during the Clayton-phase (3.6-2.0 Ma) of volcanism. The expression of Clayton-phase volcanism varies in the eastern and western portions of northeastern New Mexico. In the western part of the field, Clayton basalts cap Raton-phase basalts commonly along erosional surfaces suggesting significant time passed between the two phases of volcanism (Baldwin and Muehlberger, 1959). To the east however, Clayton basalts commonly directly overlie Raton-phase basalts, consistent with a more continuous basaltic eruption history (Stormer, 1972). Clayton-phase basalts are commonly feldspathoidal with basanitic and nephelinitic compositions but also include transitional olivine basalts (Dungan et al., 1989). Classic exposures of Clayton-phase basalts are seen at Rabbit Ear Mountain, Bible Top Butte, and Mt. Dora. Clayton-phase basanites also compose Robinson Peak and Jose Butte, just east of Capulin volcano.

Included in both the Raton- and Clayton-phases of volcanic activity is Sierra Grande, a composite volcano and the highest peak in the area. Sierra Grande is ~10 km (6 miles) in diameter and built on Clayton-phase basalt. Sierra Grande is composed of two-pyroxene andesite that only appears at Sierra Grande. Andesite flows from Sierra Grande have ages ranging from ~3.8 to 2.6 Ma (Stroud, 1997), suggesting that Sierra Grande was constructed over a ~1 million year period.

The most recent phase of volcanic activity generated Capulin-phase basalts (<2.0 Ma), with the youngest activity commonly building cinder cones centered near Capulin Volcano. Basaltic and andesitic activity is responsible for Horseshoe Crater and Malpais Mountain to the south. Activity during this phase also generated Capulin volcano, Baby Capulin, Twin Mountain, and the Purvine Hills (Ramos et al., *this volume*). In addition, silica-undersaturated volcanism generated Emery Peak on the southern flank of the Dry Cimarron. Capulin-phase basalts are mostly alkaline in composition and commonly host olivine and plagioclase phenocrysts. Many of these younger basalts have been recently dated by Zimmerer (*this volume*) to constrain the last pulse of activity and the implications for volcanic hazards of the region. Volcanic rocks at Capulin Volcano specifically define two series of petrogenetic characteristics in which one trend is similar to other young basalts in the area. With the exception of one flow from Baby Capulin, all other young eruptions in the area (i.e., Twin Mountain, Purvine Hills, and other Baby Capulin flows) share similar major, trace element, and isotopic characteristics that indicate a common magmatic source suggesting that these youngest magmas were generated and extracted from a single, magma chamber or a stable part of the magmatic system. A single basaltic flow from Baby Capulin is more primitive and likely best retains the geochemical and isotopic characteristics of the mantle underlying this region of the Great Plains (Ramos et al., *this volume*).

Located within and along the southwestern margin of the Raton-Clayton volcanic field is the mid-Tertiary Chico Hills sill and dike complex. The complex was studied as early as the 1920s and throughout the 1960s because of the presence of thorium and rare-earth element veins in the complex. Much of this and related work is summarized in Staatz (1985). Scott et al. (1990) provided additional information on the sill and dike complex as part of a reconnaissance scale investigation of the Raton 1° x 2° quadrangle. Sills and dikes of the Chico Hills complex were emplaced into Cretaceous sediments, mainly the Greenhorn Limestone and Dakota Group. As a result of emplacement, the sediments were uplifted as much as 300 m to form a broad dome over the ~360 km^2 extent of the sill and dike complex. Sparse K/Ar dating indicates protracted magma emplacement between 37 and 20 Ma, although most of the dikes and sills do not have established ages (Scott et al., 1990; Zimmerer, *this volume*). Compositions of the dikes and sills are mainly phonolitic and trachytic, with lesser amounts of syenite, trachyandestite, and other alkalic rocks. Little-studied kimberlites and intrusive breccia deposits are located southeast of Raton and may be related to the complex. Because of dissimilar ages and compositions of the Chico Hills sill and dike complex and Raton-Clayton volcanic field basalts, the two pulses of magmatism are not thought to be genetically related despite their overlapping spatial extent.

TECTONIC EVOLUTION

During the Early-Middle Paleozoic, northeastern New Mexico was located along the southern edge of the northeast-trending transcontinental arch and tectonically quiescent. By the Late Paleozoic, the development of the Ancestral Rocky Mountains created the Sierra Grande, Apishapa and Bravo Dome uplifts, separated by deeply eroded basins that were filled with clastic sediments from these uplifts (Fig. 3). During the Early Mesozoic, much of the Ancestral Rocky Mountain relief remained high throughout the majority of the Triassic (MacLachlan, 1972). By the end of the Triassic, a thin veneer of Upper Triassic sediments began to accumulate during epeirogenic subsidence of the region. During the Early Jurassic, Upper Triassic strata were subjected to compressive stress that resulted in the angular discordance between Upper Triassic and Middle Jurassic strata observed in the Dry Cimarron (Baldwin and Muehlberger, 1959) and to the south near Tucumcari. The onset of Laramide deformation in the latest Cretaceous to early Tertiary resulted in the uplift of the Sangre de Cristo Mountains and related downward deflection of the Raton Basin, which began to fill almost immediately with synorogenic sediments. Reactivation of Ancestral Rocky Mountain faults bounding the Sierra Grande and Apishapa arches resulted in these features rising. Regional epeirogenic rise during the Late Cenozoic may have occurred at the same time as development of the Rio Grande rift during crustal extension as suggested by broad warping of the Ogallala Formation to the east (Baldwin and Muehlberger, 1959; Frye et al., 1978). After orogenic deformation, volcanic centers erupted along the Jemez lineament and other zones of weakness associated with extensional forces and other structural flaws in the pre-Cenozoic rocks.

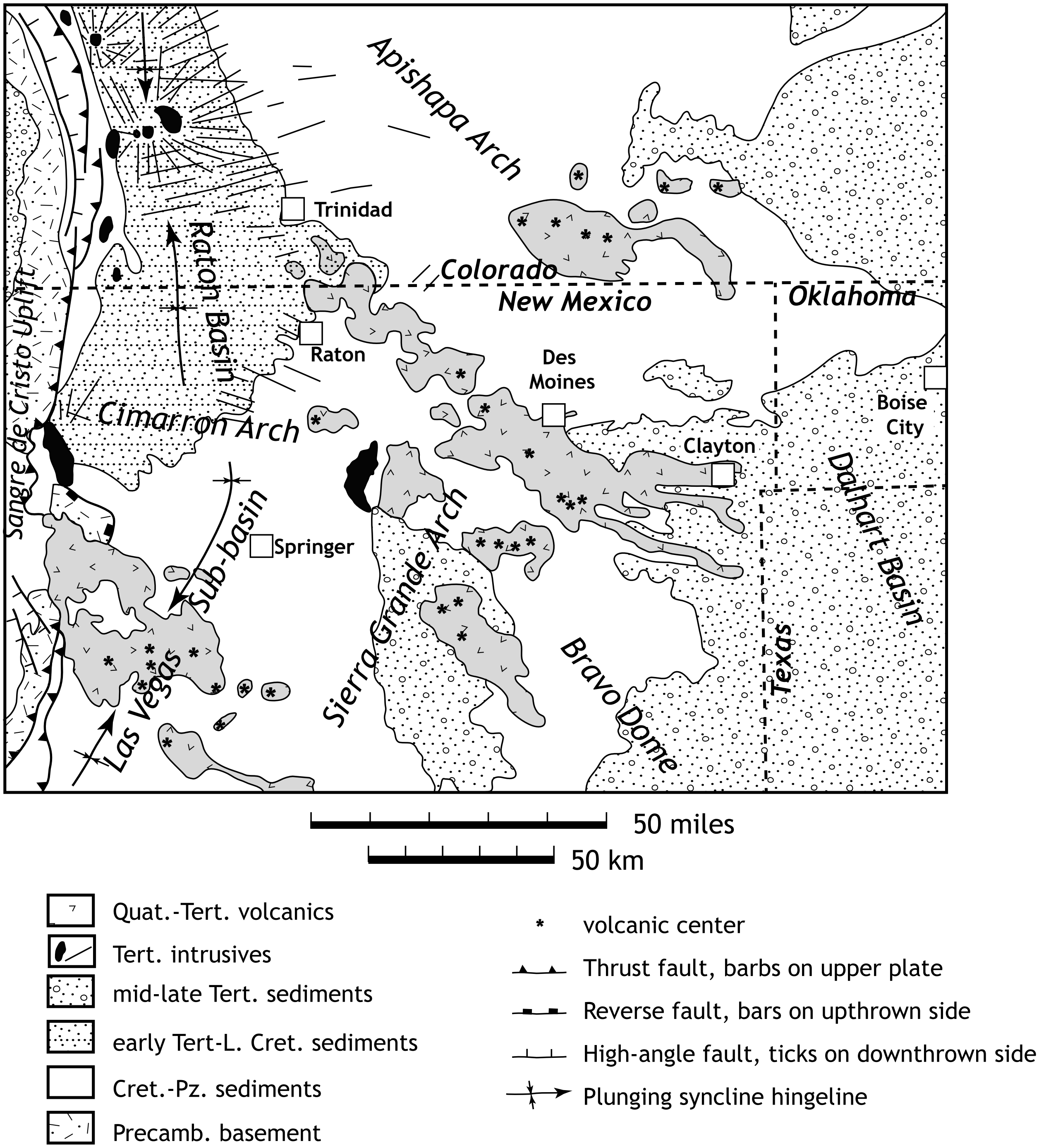


FIGURE 3. Regional tectonic map from Woodward (1987) indicating the principle tectonic features of northeastern New Mexico.

SUMMARY

Northeastern New Mexico is a land of contrasts, from the high peaks of the Sangre de Cristo Mountains to the west to the deceptive flatness of the High Plains to the east; hence the moniker "the Hi-Lo Country". This landscape, however, hosts complex geology that includes the depositional history of the Permian through the Quaternary, the history of both Ancestral Rocky Mountain and Laramide deformation, and intracontinental volcanism of the Jemez lineament related to extension of southwestern North America. The papers that follow in this guidebook represent the next phase of research in this remote corner of New Mexico and help to unlock more of the geological story hidden in this subtle landscape.

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