Celebrating New Mexico's Centennial

The geology of New Mexico as understood in 1912: an essay for the centennial of New Mexico statehood Part 3

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Introduction

The second part of this contribution, presented in the May 2012 issue of *New Mexico Geology*, discussed ideas on the absolute dating of rocks and the movement of continents through time as they were being developed a century ago, and explored the state of knowledge of New Mexico stratigraphy and paleontology as New Mexico became a state.

Here, I survey ideas and knowledge of the new state's volcanic and intrusive igneous rocks, Precambrian rocks, and geologic structure that were current in 1912.

Volcanic rocks

Volcanic rocks in New Mexico were identified by the military men coming across Raton Pass during the initial American invasion in 1846, and were reported and in some cases briefly described in many parts of New Mexico by virtually every observer who wrote about the geology or geography of the territory throughout the remainder of the 19th century. Volcanoes and associated fields of solidified lava are easily recognized, and prominent volcanoes, such as Mt. Taylor, were named as early as 1850. By 1900, with one notable exception, many of New Mexico's major volcanic features had been only briefly described, mostly as features of the landscape, but not intensively studied geologically. For example, petrographic studies, and the accurate identification of rock types within the territory's volcanic fields, were just beginning, and for many regions little to no such information was available.

The exception is the Mt. Taylor region, where both the older volcanic rocks associated with Mt. Taylor, its basalt field and smaller cones across Mesa Chivato, and the Puerco necks, as well as the much younger flows of what is now called the Zuni–Bandera field, had been studied in exceptional detail for the time. Members of the Wheeler Survey (especially G. K. Gilbert 1875), in their reconnaissance survey of west-central New Mexico, provided a brief but accurate account of Mt. Taylor and Mesa Chivato. Gilbert (1875, p. 535; see also figs. 154–157) interpreted Cabezon and other peaks correctly as volcanic necks, or casts "in lava of which the mold was the conduit of a volcano, now not only extinct but demolished." Gilbert also identified several of the flows of the Zuni–Bandera field (called the "Marcou buttes," a name that did not last), plotted the paths of the flows, and, although absolute age dating was not possible, noted that the most recent of these flows (now called the McCartys flow) is "preserved as perfectly as though cooled but yesterday" (Gilbert 1875, p. 533).

Ten years later the Mt. Taylor region was studied by Dutton (1885), who, in one of the classic works on New Mexico geology, elegantly and comprehensively described the volcanic features and the processes responsible for them. Dutton's account is a fine example of detailed field observations, assembled into evidence supporting a clearly stated interpretation of the origin and development of the volcanic structures he observed. He estimated the age of the Mt. Taylor volcanism as Miocene; although we now know it is a bit more recent (Pliocene), but his estimate was remarkably accurate for the time. Dutton emphatically showed that the younger flows of the region, such as the malpais filling the valley of the Rio San Jose, did not emanate from Mt. Taylor, as had commonly been believed before, but consisted of several distinct flows from other vents and cones. He also interpreted the flow characters of these basalts based on his observations of contemporary eruptions in Hawaii. "Some of these streams," he stated (p. 181) "may be many hundreds of years old, but others betoken such recency that we are tempted to attach some credence to the traditions of the Mexicans that when their Spanish ancestors first came to these regions they were still hot and steaming."

Darton (1916b, p. 98), observing the McCartys flow in the Rio San Jose, expressed a similar opinion of these very young-appearing basalts: "Some of the Pueblo Indians of the region have a legend, handed down for several generations, of a river of fire in San Jose valley, and it seems not unlikely that the forefathers of these people witnessed this outflow." While favoring an extremely young age for this lava flow, Darton also was rigorous in examining purported evidence for it: "It is said that the lava flowed around the corner of an old stone wall at one point above McCartys, but on inspection of this wall it appears more likely that the wall was built into an angular jog in the margin of the sheet." Seventy years later, the youngest (McCartys) flow was still regarded as a very recent event, likely around 1,000 years old or possibly as young as 400 years (e.g., Maxwell 1982). Only in the 1990s was its age determined by radiometric means to be around 3,000 years B.P. (e.g., Dunbar and Phillips 2004). Elston (pers. comm., 2011) noted the tantalizing possibility that black cinders associated with Bandera crater (most of which is composed of petrologically different red cinders about 10,000 years old) might be much younger, as pueblo artifacts dating at A.D. 700–900 reputedly were found below the black cinders.

Near the time of statehood, Douglas Johnson studied the Puerco necks (Johnson 1907), examining 17 of them in detail and providing some outstanding photos of individual necks (Fig. 15). His aim was to re-evaluate the field evidence for their origin, as such features elsewhere were being interpreted as the eroded remnants of laccoliths or as small remnants of thick extensive lava flows,

Editors' note

In honor of New Mexico's centennial celebration, *New Mexico Geology* has dedicated this volume to the accomplishments of geologists working in New Mexico Territory from 1846 until statehood in 1912. This contribution will be published in four parts, one in each of the four quarterly issues of the 2012 volume of *New Mexico Geology*. References are included for each part, and the numbering of figures is consecutive from part to part.

FIGURE 15—Cerro Cochino neck from the west, “showing undisturbed sediments well up towards top of butte” (Johnson 1907, fig. 1).

based on the common presence of columnar jointing. He fully corroborated Dutton’s interpretation of these peaks as volcanic necks. Johnson had studied under Herrick and received in 1901 the first bachelor’s degree in geology awarded by the University of New Mexico. He then went to Columbia University, receiving his doctorate in two years (for his study of the geology of the Cerrillos Hills, see part 2), then taught at Massachusetts Institute of Technology and Harvard before becoming a professor at Columbia (in 1912), where he remained for the rest of his life. At the time of his death in 1944, he was arguably America’s foremost geomorphologist, an authority on coastal geology and the Appalachian Mountains, and a specialist in military geography (Northrop 1966).

In northeastern New Mexico, the only (brief) study of the widespread volcanism of the Raton–Clayton field was by R. T. Hill (e.g., 1892), a USGS geologist who mainly worked in Texas. Hill gave a brief summary of these volcanic rocks, and recognized (p. 99) that “the beautiful cinder cone” of Mount Capulin and neighboring cones were “clearly of a more recent origin than the adjacent basaltic cap of the Raton plateau, for they are situated in an eroded valley between the main mesa and outlier…and at a considerably lower elevation than either of them. They are also apparently more recent than the late Tertiary deposits of the Llano Estacado, the original surface of the lava resting upon the latter and not covered by it…” Capulin Mountain, dated at 56,000 years (Muehlberger et al. 2010) is indeed considerably younger than the other volcanic flows of the Raton–Clayton field. Years later Willis Lee (1912c), while studying the Cretaceous–Paleocene stratigraphy of the coal-bearing rocks of northeastern New Mexico, also examined the volcanic rocks of the Raton–Clayton volcanic field. He too was especially impressed with Capulin Mountain as a magnificent example of a recently extinct volcano, and recommended that it be made a national monument. Four years later (August 1916) President Woodrow Wilson by proclamation designated Capulin Mountain National Monument.

Some unusual volcanic structures were also studied in some detail before 1912. Zuni Salt Lake, 16 miles northwest of Quemado, in northwestern Catron County, was visited briefly by Gilbert (1875, pp. 538–539), who was aware of its historical importance as a source of salt used and traded by Native Americans and early Spanish colonists. He briefly described this “basin,”as a deep depression surrounded by Cretaceous strata except for basalt along one end, and possessing a well-developed cinder cone (Gilbert mentioned one cone; actually there are two). He found this structure “anomalous in character, and…its origin is inexplicable.” Herrick (1900a) also visited the lake and described it in more detail. He was more interested in the details of salt deposition than the origin of the depression, but in passing attributed it to a volcanic conduit that had been left open when the eruptions stopped, or which once had possessed a neck that subsequently was removed during subsidence into (hypothetical) underlying salt beds. Dissolved salts from underground presumably migrated to the surface with movement of water through the conduit.

A little later Darton (1905), in his first published paper on New Mexico geology, provided photos and a geologic map and cross section of the Zuni depression, and noted (p. 190) that its “origin and history are an interesting problem” as it “presents none of the ordinary features of a crater.” His geologic map (fig. 2) shows the two scoriaceous cones within the lake, the rim around the lake composed of Cretaceous sandstones capped on its north, east, and southeast sides by lava, and surrounded by a wide area of “volcanic ejecta” covering the Cretaceous bedrock. Darton’s interpretation (p. 192) was that the depression resulted from “a great ejection of hot water from a central vent, which dissolved a great mass of salt,” and which brought to the surface and spread in all directions many volcanic rock fragments. After the eruption, the circular depressed area formed by subsidence into the space opened by the solution of subsurface salt and by ejection of volcanic debris. More recent work indicates that Zuni Salt Lake is the result of an explosive volcanic steam and magma eruption (maar) about 90,000 years ago. The salt, rather than being derived from subsurface deposits (for which there is no evidence), is now interpreted as having formed from the evaporation of a larger lake that formerly filled the crater (Crumpler and Aubele 2001).

Another curious volcanic structure caught the attention of Willis Lee during his reconnaissance field studies in and around the Rio Grande valley. He visited the volcanic craters south of the railroad siding of Afton, southwest of Las Cruces, referring to them as the Afton craters; they are now known as Kilbourne and Hunts Holes. Lee (1907c) provided a map, cross section, and description of Kilbourne Hole (Fig. 16), paying particular attention to the mix of basalt, pumice, cinders, and sand that compose its rim, and its position on the La Mesa geomorphic surface. He ascertained the young (Pleistocene) age of the unconsolidated sediments below the crater, and field observations of the basalt flows and volcanic caves in the area led him to correctly identify two episodes of eruption, both occurring “long after the opening of the Pleistocene” (p. 216).

Lee considered four hypotheses for the origin of these depressions: meteorite impact, volcanic subsidence, solution subsidence, and explosion of steam owing to volcanic activity. In his view, the evidence strongly favored explosions “caused by the sudden

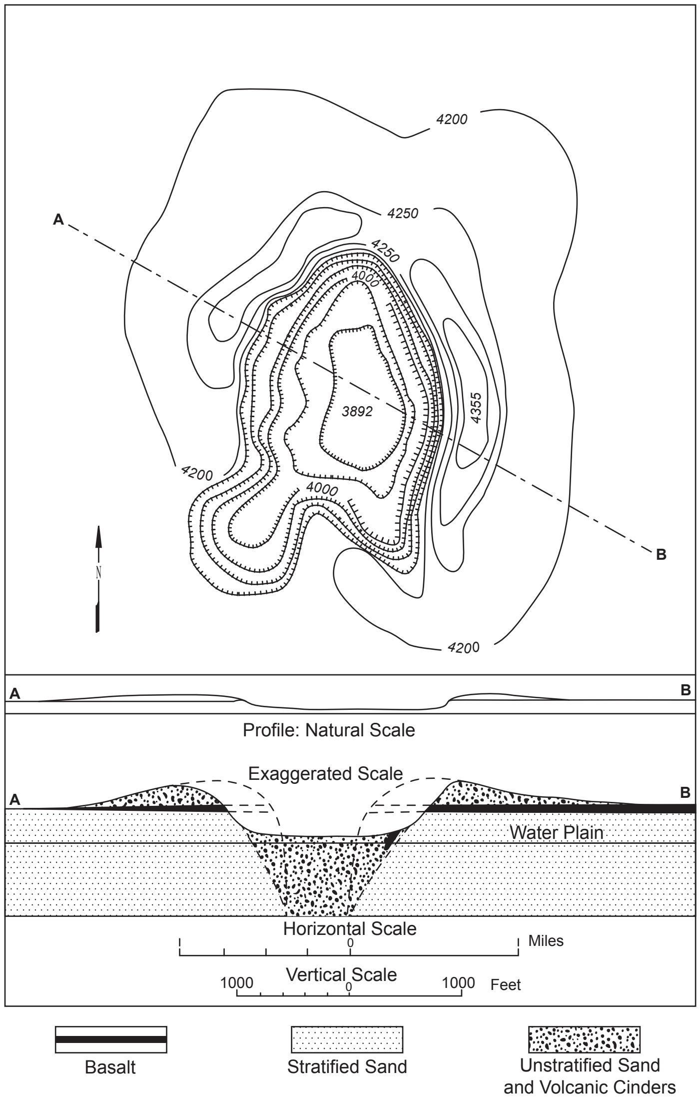

FIGURE 16—One of the “Afton craters” (Kilbourne maar). Redrawn from Lee (1907c, fig. 1).

conversion of water into steam, following the entrance of molten lava into the water-saturated sands” (p. 218). This interpretation proved to be essentially correct; augmented by much subsequent work (see Seager 1987) and more emphasis on caldera-like collapse features, these are now recognized as maar craters.

Lee believed that these depressions “represent one of the first stages of volcanic activity in the district,” with later eruptions filling some depressions and eventually building volcanic cones. Later work has indeed shown that these craters formed during the earliest volcanic eruptions (Afton basalts) in the area (about 66 to 120 ka), which were followed by the cones and flows of the Aden basalt field (e.g., Hoffer 1975; Hoffer et al. 1998).

In central New Mexico, including the Albuquerque and Socorro areas, much of the geologic information available in 1912 was the result of reconnaissance surveys conducted by C. L. Herrick just before and during his short term (1897–1901) as president of the University of New Mexico. His main publications on the geology of the Albuquerque area (Herrick 1898a, c; Herrick and Johnson 1900), Socorro area (Herrick 1898b, 1900a, 1904a), and the Tularosa Valley (Herrick 1900b, 1904b) typically provide generalized observations of the regional or local geology, punctuated with detailed descriptions of some features and attempts at synthesis of the structural, stratigraphic, geomorphic, and igneous history of an area. Among his contributions were the first reasonably detailed geologic maps of the greater Albuquerque area (Herrick 1898b, Herrick and Johnson 1900) and the Tularosa Valley (Herrick 1900b). Herrick realized that many of his observations and interpretations were preliminary (his papers have many references to more detailed studies in progress or anticipated, which were never completed because of his untimely death), but much of his work also represents the first accurate (and in some cases very perceptive) geologic description and interpretation available for the areas he inspected, and form the starting point for later work in subsequent decades.

Herrick began his reports on the geology of the Albuquerque area by expressing surprise “that the geology of the valley of the Rio Grande in New Mexico seems to have escaped attention while the more inaccessible parts of the territory have been the subject of elaborate memoirs” (Herrick 1898a, p. 26), and noted that his studies, carried out in intervals of the administrative work of the university “cannot hope to be exhaustive.” Still, with respect to the volcanic geology, he provided reasonably detailed and accurate descriptions of the Albuquerque volcanoes, noting that they are older than the river gravels but younger than the sandy sediments (thought incorrectly to be Cretaceous initially but soon, in Herrick and Johnson 1900, revised to Tertiary) composing the mesa to the west (Llano de Albuquerque). He also accurately described (1) Isleta volcano (noting evidence of explosive eruptions, quoted in Kelley and Kudo’s [1978] modern study of the Albuquerque area volcanism); (2) the detached basalt flow on Paria (Black) Mesa nearby; (3) the dikes and plugs of the Canjilon Hill diatreme (called Bernalillo volcano by Herrick 1898a, whose photo of the “Octopus plug,” fig. 1, is nearly identical, though from the opposite direction, to Kelley and Kudo’s 1978 photo, fig. 8); and (4) the superposed flows of the San Felipe field atop Santa Ana Mesa. Herrick wrestled, only partially successfully, with the ages of these basaltic rocks, in terms of their perceived relationships with the various facies of the ancestral Rio Grande fluvial deposits, and he concluded that they are all post-Tertiary (Herrick and Johnson 1900, p. 6), because they rest upon Tertiary strata. He also stated, somewhat contradictorily, that there is no evidence that any of the lavas flowed over river deposits of presumed Pleistocene age (probably he meant late Pleistocene age). Peralta (Los Lunas) volcano was considered to be instructive in this regard, as Herrick observed no trace of the lava field associated with the cone remains, the lava having been eroded away or buried by an earlier version of the Rio Grande. The possibility of the Isleta flow postdating the appearance of humans was cautiously entertained (Herrick 1898a, p. 28), based on the supposed occurrence of charred maize beneath the lava flow, but this idea was dispelled 2 years later (Herrick and Johnson 1900).

Before arriving in Albuquerque Herrick had resided in Socorro, and in one early paper (Herrick 1898b) he described at length the geology of the Socorro, Lemitar, and Magdalena ranges, together with interpretation of their geologic history and structural development. Space does not allow detailed analysis of his observations in light of modern knowledge, but a few comments are pertinent. He recognized remnants of Pennsylvanian limestones in all three ranges. In the mountains around Socorro he noted a complex series of andesite flows beneath trachyte and rhyolite flows, and great masses of breccia and talus conglomerates, all of which suggested to him that volcanic activity had been explosive. One trachyte flow, composing the steep ridge near the crest of Socorro Peak, was said to form “the northern wall of an ancient crater of great extent” (p. 76), probably the first mention by any geologist of a large crater in New Mexico (Elston, pers. comm., 2011). Studies beginning more than seven decades later would eventually interpret most of the volcanic rocks observed by Herrick as remnants of the large Socorro caldera (e.g., Chamberlin et al. 1987). Basalt flows observed southwest of Socorro (Herrick, 1898b, pp. 78–79) are now known to be younger products of the rift-related Socorro Peak volcanic center.

Similarly, Herrick (1898b, see text and fig. 5) interpreted the Lemitar Mountains as the result of a massive volcanic eruption that tilted the Carboniferous strata westward and produced voluminous flows of rhyolite, trachyte, andesite, and tuff. Herrick believed (p. 64) that volcanic activity was also responsible for the metamorphism of sandstone and conglomerate into the schist, gneiss, and granite that compose a significant part of the range, and which are now known to be Precambrian basement rock. Such an interpretation seems strange today, but readers should recall that a metamorphic origin for granite was seriously advocated early in the 20th century (see Elston 2001, p. 52 for discussion and also for commentary on the evolution of knowledge regarding the caldera/ignimbrite origin of many of the volcanic rocks that Herrick was trying to make sense of in this area).

Herrick's studies of the Magdalena Mountains reported limited west-dipping late Paleozoic strata on the northern end of the range and "underlying metamorphic granite and quartzite on the more abrupt and irregular eastern slopes" (p. 88), which were later identified as Precambrian by Lindgren et al. (1910). The dominant rock types through the remainder of the Magdalenas observed by Herrick were andesite flows emanating from what he believed were two craters at Big and Little Baldy peaks, and overlying extensive explosively erupted trachyte, obsidian, tuff, and rhyolite flows, apparently from fissures. Faulting along the north end of the range was thought to be mainly responsible for its uplift. Lindgren et al. (1910) provided additional details on these three ranges, written in a more coherent fashion, but basically followed the interpretations of Herrick. Herrick's studies of the volcanic rocks of the Albuquerque and Socorro areas were regarded as authoritative for several decades (e.g., Darton 1928, p. 64).

The most accurate and comprehensive account of volcanic rocks in New Mexico (as well as other areas of geology) at the time of statehood was Lindgren et al.'s (1910) treatise on the ore deposits of the territory. This survey of metal-producing districts throughout New Mexico not only incorporated previous knowledge of the geologic context of the mining areas, but presented many new observations based on extensive field surveys, and sought to synthesize this information into models explaining the overall geologic history of the territory. For the first time (for New Mexico) igneous rocks and their relationships were not only described in the field but samples were analyzed in the lab for petrographic and chemical data. These analyses were far more abundant and important for the intrusive rocks with which most orebodies were associated (see next section).

New observations and interpretations were presented for many areas. In the Jemez Mountains, Lindgren et al. (1910, p. 151) reported that over the pre-Tertiary surface "there were extruded a great flow of rhyolite," 500 to 800 feet thick (now called the Bandelier Tuff), of probable Miocene age (actually it is Pleistocene). This rhyolite "had its source at a vent somewhere in the vicinity of Pelado [Redondo Peak], a conical pile over 11,200 feet high…" Pelado and other peaks in the area "are probably parts of a considerably dissected volcanic cone, which had a diameter of 15 miles and was made up of ash, cinder, and other ejecta." Surrounding Pelado Peak was a "broad, outsloping border; averaging about 10 miles in width," and this "bordering apron…is simply divided into many narrow segments by sharp deep canyons cut by radiating streams that head against the higher cone; …the divides that separate them are gently inclined planes which doubtless closely correspond to the original flow surface of the rhyolite." This is the first real geologic description of the Valles caldera and Pajarito Plateau, elegant in its simplicity and general accuracy.

Lindgren et al. (1910) also briefly described the volcanic geology in several areas of the Mogollon–Datil area, where important ore deposits occur. They described the Mogollon Mountains, for example (p. 192), as being composed mainly of rhyolite, with some andesite, and "…alternating with quiescent flows of molten rock that spread away from vents and produced massive beds of these rocks were explosive outbursts of shattered and comminuted rock that fell back to the surface as breccia and tuff. The thickness of the flows and tuffs undoubtedly aggregates some thousands of feet." Lindgren et al. found that individual lava sheets were relatively thin and the entire region to be heavily faulted.

Similarly, the Black Range was described as a great thickness of andesite, consisting of flows, tuffs, and breccias, with its eroded surface covered with rhyolite and rhyolite tuffs (p. 262). They also reported that rhyolites were greatly developed in the San Mateo Mountains south of Socorro, with that range consisting "wholly of rhyolite with its associated breccias, tuffs, and devitrified glass." As brief and nonsynthetic as they are, these observations do provide an early indication of the dominant geologic processes affecting the geology of the Mogollon–Datil and neighboring areas. It would take more than a half-century for the origin of these rocks in many late Eocene–Oligocene calderas to begin to be understood (see Elston 2001; Chapin et al. 2004).

Lindgren et al. (1910, pp. 42–46) synthesized what was then known about the volcanic history of New Mexico, recognizing a sequence of four middle Tertiary to Quaternary eruptive episodes: rhyolite, andesite/latite/trachyte, more rhyolite, and basalt. The temporal order of the first three stages was not everywhere distinct, and together were thought to represent a second major period of igneous activity, following an early Tertiary episode of widespread intrusions. Massive outpourings of rhyolite and rhyolitic tuffs were said to characterize the Jemez, San Mateo, and Mogollon Mountains, as well as the Black Range and Silver City area. Thick andesites were observed in the Socorro area, Black Range, Mogollon Mountains, and other areas of southwestern New Mexico, in some places directly beneath the main rhyolite flows. Some andesite lavas were also reported from the Mt. Taylor field.

The last major phase of volcanism occurred in the late Tertiary and Quaternary, and produced many geologically young basalt fields, with many preserved volcanic cones, across the territory. The large basalt fields near Raton and east of the Mora uplift (Ocate field), and those observed almost continuously along the Rio Grande valley from the Colorado state line (Taos volcanic field) to Albuquerque and resting on the "Santa Fe marls" were attributed to this episode. So too were the eruptions of Mt. Taylor and the more recent Zuni–Bandera field, the 50-mile-long flow on the east side of the Oscura Range (Carrizozo flow), and many smaller fields around Albuquerque, Socorro, San Marcial (Jornada flow), Elephant Butte, and Rincon (southern Caballo Mountains), as well as the Afton craters and flows southwest of Las Cruces. Lindgren et al. (1910, p. 45) concluded that although "it is not believed that all the larger basalt flows are of the same age, it is clear that all the basalts are comparatively recent and that there was a considerable interval between the late rhyolite and the basalt." In some places, such as the southern reaches of the Rio Grande valley, at least two episodes of basaltic volcanism could be distinguished based on stratigraphic relationships with the valley-fill sediments ("Palomas gravels"), the youngest being the post-Palomas Jornada and Potrillo basalt fields. Even younger flows, of Recent age, some believed to be possibly only a few hundred years old, included those in eastern Socorro and Otero Counties, and in western Doña Ana and Valencia Counties.

Nearly a century of subsequent studies have modified most of these broad generalizations and our understanding of the timing of volcanic events in New Mexico. The advent of radiometric dating of volcanic flows, a far more detailed understanding of the development and history of the Rio Grande rift, and the discovery of many Paleogene calderas, accompanied by deciphering their structures and eruption histories, have been especially instrumental in furthering our understanding of the state's history of volcanism.

Intrusive rocks

Before 1900 little detailed information was available concerning intrusive igneous rock bodies in New Mexico, beyond very general reports and a few moderately detailed local observations. Lindgren et al. (1910), however, paid a great deal of attention to intrusions because much significant mineralization was associated with them. For many mining districts, Lindgren et al. presented extensive descriptions of intrusive bodies, together with detailed analysis of their mineralogy often accompanied by chemical analyses. In addition, they reported on the geology and mineralogy of such features as contact metamorphism and other zones of alteration between an intrusion and the country rock surrounding it, as well as describing smaller structures such as dikes associated with primary intrusions, veins, mineral zones, and alteration processes occurring within the intrusions. The amount of detailed information on igneous intrusive bodies presented by Lindgren et al. (1910) increased knowledge of this important aspect of New Mexico's geology probably by an order of magnitude or more over what had been known before and formed the starting point for much subsequent research.

The absence of radiometric dating methods made determining precise ages of intrusive bodies difficult, and age determinations relied mainly upon crosscutting relationships with the surrounding intruded country rock. In general, Lindgren et al. recognized two major episodes of intrusive activity in New Mexico—in the Precambrian (see Precambrian section, p. 72), and in the early Tertiary. The early Tertiary episode was thought to have accompanied major mountain building and uplift throughout much of New Mexico, including those ranges that rose along faults to form what is now known as basin-and-range and Rio Grande rift topography. This intrusive activity was believed to have preceded the eruption of voluminous andesitic and rhyolitic lavas and tuffs that covered much of the area between Socorro and Silver City as well as other areas such as the Jemez Mountains.

According to Lindgren et al. New Mexico's early Tertiary intrusive rocks took the form of laccoliths, stocks, sheets (sills), and dikes, and they display a remarkable uniformity of composition, intermediate between granite and diorite. Although a few true granodiorites and diorites were observed, the composition of most intrusions was believed to correspond closely to monzonite or quartz monzonite or their porphyries. Intrusions in the Red River and Cimarron areas, near Cochiti, in the Cerrillos Hills, the Ortiz and San Pedro Mountains, the Socorro and Magdalena ranges, and near Hillsboro, Kingston, and Silver City were described in detail. So too were large isolated eroded intrusions, such as Cookes Peak, and smaller masses, often with dikes, in the Burro, Hachita, and Peloncillo Mountains of the southwestern part of the territory. Farther east, in Lincoln County, intrusions composing the White Mountains (Sierra Blanca) and in the Nogal, Jicarilla, and White Oaks districts were discussed. They noted that the Organ Mountains represented an intrusive body of unusual size. Diorite porphyries in the Kimball (Steins Pass) and Lordsburg districts appeared to be of uncertain age, perhaps as old as Late Cretaceous (p. 42).

Although these intrusions cut through rocks of a wide variety of ages, from Precambrian to Cretaceous, most were said to display doming of the overlying sedimentary strata in laccolithic fashion. Other conclusions presented by Lindgren et al. (1910, p. 41) included the ideas that (1) "intrusion took place against a heavy load of superincumbent strata and that connections with the surface were not easily established"; (2) "that a great epoch of erosion took place between the intrusion of these rocks and the great lava flows of the middle Tertiary," suggesting that "the lavas have no direct relationship with the intrusive rocks"; and (3) that by the end of the Cretaceous Period, "practically the whole of New Mexico was covered by a thick mantle of sedimentary rocks, the total thickness of which was 6,000 to 9,000 feet," leading to an estimate (based on the stratigraphic position of rock intruded by various magma bodies) that the intrusions ranged in depth from 2,000 or 3,000 to 9,000 feet below the early Tertiary surface.

The conclusions of Lindgren et al. (1910), although representing an excellent contemporary view of the relationships of intrusive bodies to stratigraphic and structural features in New Mexico in the years just before statehood, have been refined considerably and modified through the following century. We now know, for example, that although some intrusive bodies (stocks, sills, dikes) in the Silver City, Hillsboro, and Little Hatchet Mountains regions range in age from Late Cretaceous to early Eocene (McMillan 2004), most of the major intrusions discussed by Lindgren et al. are younger (late Eocene–Oligocene; see Chapin et al. 2004, table 1, fig. 2). Thus, this intrusive activity largely overlaps with, and many are genetically related to, the voluminous rhyolite, andesite, and ignimbrite eruptions that Lindgren et al. believed represented a significantly later (mid-Tertiary) episode of igneous activity.

Similarly, Lindgren et al.'s (1910) correlation of the major intrusive episode with most of the Cenozoic mountain building in the state, including basin-and-range faulting, is now known to be inaccurate. Most major intrusive activity, as well as rhyolite/tuff (caldera) volcanism, followed earlier Laramide mountain building but preceded the later crustal extension that produced the basin-and-range uplifts and the Rio Grande rift. This probably could not have been ascertained in 1910, in the absence of radiometric dating of the igneous rocks and without a conceptual framework that recognized the great differences between the earlier Laramide and more recent basin-and-range structural/tectonic regimes. As Lindgren et al. (1910, p. 33) admitted, "[k]nowledge concerning the mechanics of mountain-building is somewhat uncertain…"

Finally, the belief of Lindgren et al. that New Mexico was uniformly covered by 6,000 to 9,000 feet of sedimentary rocks at the end of the Cretaceous, and that (p. 32) intrusions "were forced in underneath the pliable and tough mantle of Cretaceous sediments, bulging it in laccolithic fashion" is, in the later light of a century of subsequent knowledge, very simplistic. In reality, although some parts of the territory consisted of tectonically undisturbed sequences of Paleozoic and Mesozoic strata at the end of the Cretaceous, the onset of the Laramide orogeny in Late Cretaceous time was beginning to produce major crustal deformation in the form of faulted uplifts and complementary sediment-accumulating basins. Highly irregular topography and complex surficial geology characterized much of New Mexico by the time of the onset of major intrusive and caldera activity in late Eocene time (e.g., Seager 2004; see also the Structure section, p. 72). Mid-Cenozoic intrusions penetrated a variety of rocks, and few if any formed laccolithic bulges against overlying horizontal deposits of Cretaceous strata. The depth at which the intrusions were emplaced varied far beyond the 2,000 to 9,000 feet visualized by Lindgren et al. (1910).

One consequence of this simplistic view of the depth of these intrusions was a consistent overestimation of the depths of emplacement of magmatic-hydrothermal ore deposits. Elston (pers. comm., 2011) wondered "whether these overestimates were L. C. Graton's doing. In the sections of Professional Paper 68 attributed to Graton, andesite lava flows are consistently misidentified as diorite porphyry plutons…This would sink associated ore deposits with "mesothermal" mineral assemblages into their "proper" depth of 1,200–4,500 m, even where field evidence puts them near the surface."

In the years leading up to statehood, mining around the Paleogene intrusions of the Silver City region of Grant County produced more metal resources (copper, gold, silver, lead, zinc) than any other area in New Mexico territory, rivaled only by Socorro County. Lindgren et al. surveyed the major mining districts in 1905 and provided reasonably detailed summaries in their "ore deposits" monograph (1910), but the need for more extensive and detailed study of this important metal-producing region was apparently recognized by the USGS.

Even before Lindgren et al. (1910) was published, the survey sent Sidney Paige to study the geology and mineral deposits of the mining districts in the Silver City area. Paige, who attended the University of Michigan (1901–1903) but without receiving a degree, had been hired by the USGS in 1903. He had a long career with the survey (1903–1926), working in Alaska, central Texas, and South Dakota as well as in New Mexico, served on the Panama Canal Commission (1907), with the U.S. Army Engineers (1935–1946), and as a visiting professor of engineering geology at Columbia University (1946–1958). In southwestern New Mexico Paige studied the geology and mineral deposits of several major mining districts, including Hanover (Paige 1909), Pinos Altos (Paige 1911a), the Burro Mountains (Paige 1911b), and Santa Rita (Paige 1912a). Much of this work was brought together in his USGS Silver City folio (Paige 1916).

Paige's studies of these districts added considerably to the information provided by Lindgren et al. (1910). Typically he thoroughly discussed the geology of a district, with special attention to the dimensions, mineralogy, and structural relationships of intrusive igneous bodies and associated country rock. He described in great detail the veins and other mineralized zones in the district, often on a mine-by-mine basis, relating them to the history of major intrusions, local structures such as dikes and faults, and subsequent processes producing alteration of original mineral deposits. Probably his most important and fundamental contribution, however, was his clear definition of different episodes and types of mineralization and the local geochemical conditions that produced them, and his correlation of these with the local and regional geologic history of a district. He also studied the geology of the noted turquoise deposits in the Little Burro Mountains. Turquoise filled cracks in veins in altered Precambrian granites and was deposited as nodules in a kaolinized matrix (Paige 1912b). Contrary to an earlier view that the turquoise formed as a result of solutions ascending from a deep-seated source, Paige marshaled evidence that demonstrated the turquoise was a product of the zone of oxidation, influenced by descending surface waters. As a result of Paige's studies, when New Mexico became a state the geology and genesis of the ore deposits in the Silver City area were better understood than those of most other major mining districts in the country.

Precambrian rocks

Before 1900 Precambrian rocks were generally called "basement" or "primitive" rocks. Toward the end of the 19th century, they were labeled "Archaean" or Archaeozoic, but studies across North America were beginning to differentiate earlier from later pre-Cambrian rocks. The term Proterozoic was introduced in 1888, but despite Chamberlin and Salisbury's (1906) recommendation that it be limited to the interval between the Archaeozoic and Paleozoic (the present usage), the USGS used Proterozoic essentially as a synonym for Precambrian until around 1925 (e.g., see Darton's 1916 time scale, Fig. 5 in part 2). Most geologists of the early 20th century, like Lindgren et al. (1910), simply used pre-Cambrian for these oldest rocks in a region.

By 1900 Precambrian rocks had been identified in many mountain ranges in New Mexico, typically overlain by thick sequences of Paleozoic strata. Because they lacked fossils and rudimentary dating was only possible by their superpositional or crosscutting relationships, and because they contained few economically valuable ore deposits, they attracted little interest. The only fairly extensive and reasonably detailed account of Precambrian rocks in New Mexico before the 20th century formed part of Stevenson's (1881) voluminous study of the Sangre de Cristo Mountains.

As for other areas of New Mexico geology, Lindgren et al.'s (1910) treatise on the ore deposits of the territory brought together scattered previous descriptions of Precambrian rocks and added new information, derived both from field observations of the rock bodies and in some cases detailed petrographic examination. They identified and briefly described "pre-Cambrian" rocks in several parts of the Sangre de Cristo (e.g., Picuris, north Las Vegas, Taos area, Santa Fe range) Mountains, in the Nacimiento, Zuni, and Sandia Mountains in the northern part of New Mexico, and in the Oscura, San Cristobal (Fra Cristobal), Caballo, Magdalena, Florida, Burro, and Peloncillo Mountains in the south. They also noted (p. 29) that the "quartz monzonite of the Organ Mountains, which by most geologists has been regarded as pre-Cambrian" is shown by their observations "to be intrusive into the Paleozoic limestone." They were correctly referring to the Eocene granites of the Organ batholith (pp. 206–208), which are exposed in association with Paleozoic strata along San Agustin Pass, on the northwestern side of the range (Seager 1981). However, a large area of Precambrian granite is present north of the pass to the east, which their reconnaissance of the mines in the area apparently did not traverse. Readers interested in the details of the rock types encountered in each of their Precambrian localities are encouraged to examine Lindgren et al.'s (1910) accounts, which comprise the first authoritative information on Precambrian rocks in some of these ranges.

At this early stage of investigation of the New Mexico Precambrian it was "obviously impossible to connect all these observations so as to form a consistent theory in regard to the pre-Cambrian history of New Mexico" (Lindgren et al. p. 29). However they did propose a very general synthesis (pp. 27, 29). "The oldest rocks observed are quartzites, mica schist, and limestone." These early metamorphosed sedimentary units were "invaded and broken, in some places almost to obliteration, by enormous masses of normal, usually reddish, microcline granite. In most but not all places a schistocity, varying greatly in intensity, has been produced in this granite. At a few places the granite also breaks through or contains remnants of older greenstone tuffs, amphibolites, and rhyolites." The granitic intrusions, in turn, have "been intruded by dikes and masses of diorite rocks. In some places these dioritic rocks are cut by pegmatite dikes and a later granite. Schistocity in various degrees has been produced in both sediments and igneous rocks." The Precambrian rocks observed in New Mexico were believed to correspond in age with those in various parts of Colorado, but to be older than the "Grand Canyon Series" (late Proterozoic rocks) in Arizona.

A century of subsequent work has resulted in an incomparably broader, richer, and more detailed knowledge of New Mexico's Precambrian rocks. Most information compiled through the 1950s was descriptive and completed in the context of local geologic and mapping studies. With the availability of early U-Pb and Rb-Sr ages in the mid-1960s, study of Precambrian rocks expanded and began to focus on the genetic and tectonic implications of the various Precambrian terranes across the state. Still, even by the time of the first notable synthethic study of Precambrian rocks in central and southern New Mexico (Condie and Budding 1979), these authors (p. 48) commented that the "tectonic setting of Precambrian rocks in the Southwest is poorly known." Studies since then have broadened even more, integrating the New Mexico Precambrian record into the larger context of the Proterozoic evolution of continental lithosphere in the western U.S. from 1.8 to 1.0 billion years ago, and into a regional understanding of the large and small plate tectonics processes that produced or influenced the wide variety and ages of Precambrian rocks now known to exist on the surface and in the subsurface within New Mexico (see Karlstrom et al. 2004, for a recent synthesis). It is worth pointing out that Lindgren et al.'s (1910) recognition of an earlier metamorphic event, followed by widespread intrusion of granitic magma with accompanying metamorphism, is reflected in the two main orogenic events (1.80–1.65 and 1.45–1.35 billion years ago) now known to be recorded in New Mexico's Proterozoic rocks (Karlstrom et al. 2004, p. 24).

Structure

Many 19th century geologists working in New Mexico recorded their observations of the structural features and geologic history of the areas they studied, and some included simple structure cross-section diagrams to portray their interpretations. Faults and folds, the dip of strata, and unconformities were basic pieces of information recorded by field geologists by the turn of the 20th century, and the more comprehensive publications also offered interpretations of the apparent structural history of prominent features of the landscape (Fig. 17). The late 19th century also witnessed many theoretical explanations of regional mountain-building processes and the beginning of recognition of the causes and timing of major tectonic events across North America.

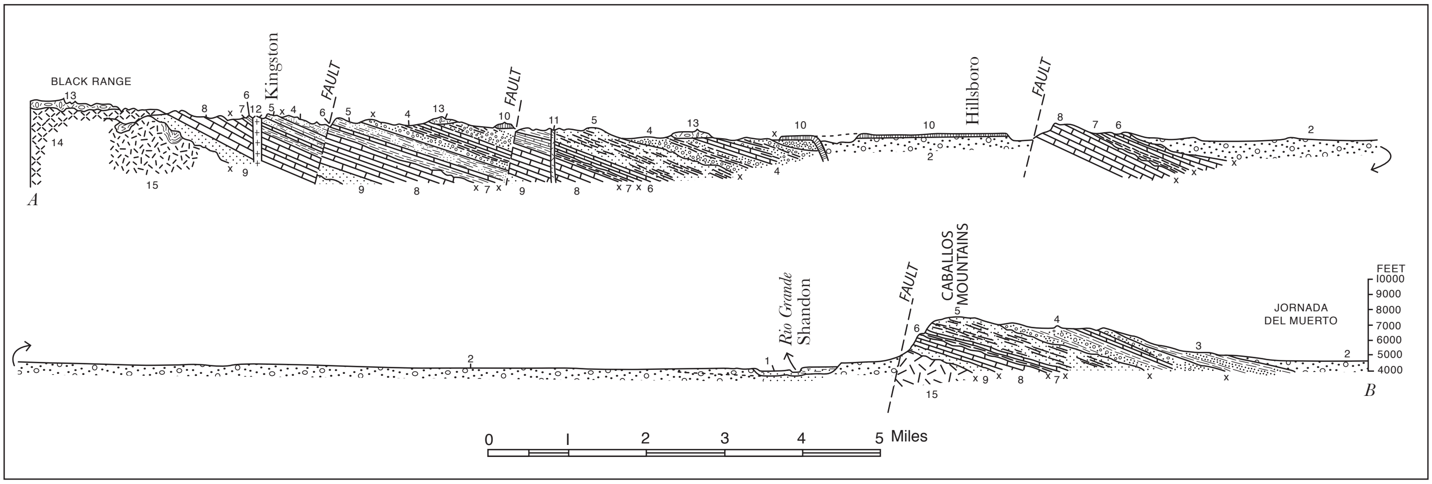

FIGURE 16.—Profile section from Kingston to Jornada del Muerto (along line *A-B*, P1. XII). 1. Lower terrace and flood-plain deposits; 2. Palomas gravel; 3. Cretaceous; 4. Manzano group; 5. Magdalena group; 6. Lake Valley limestone; 7. Percha shale; 8. Mimbres limestone; 9. Shandon quartzite; 10. basalt; 11. granite porphyry; 12. quartz monzonite porphyry; 13. rhyolite; 14. andesite; 15. granite and schists; x, erosion unconformity.

FIGURE 17—Example of a detailed regional cross section (from the Black Range east to the Jornada del Muerto) that accompany many early 20th century papers on New Mexico geology (redrawn from Lindgren et al. 1910, fig. 16).

The underlying causes of uplift and mountain building were subjects of much interest to late 19th century geologists. The influence of "gravitational equilibrium" in adjusting the surface of the earth had long been recognized; the term *isostasy* for these adjustments was coined in 1888 by C. E. Dutton (of Zuni Plateau fame). Continents rise high, for example, because they are less dense than the crust of the ocean basins.

Mountain building was generally explained as a process associated with deposition of thick sequences of sediments in linear troughs called geosynclines, which warped the underlying crust downward and produced linear bulges (geanticlines) in the thinner sedimentary sequences along their margins. Lateral pressures within a geosyncline, thought by many to be generated primarily by contraction of the earth's crust as its interior cooled, produced folds, faulted ridges, and other types of deformation, contributing to the elevation of mountain chains in the area of the geosynclines. Volcanic activity and the intrusion of large masses of magma also contributed to uplift locally, as did the forces of denudation thatcould, according to some workers, erode the thinner geanticlines down and accentuate the thicker geosynclinal sequences as the high areas of topography (see Dana 1894, pp. 376–391; Schuchert 1924; and Dunbar and Rogers 1957, pp. 309–315 for details). Refinement of these basic ideas formed the paradigm for mountain building until the advent of plate tectonics in the 1960s and 1970s.

At the time of New Mexico statehood structural interpretations based mainly on field mapping and related studies were beginning to be formulated in some detail for broad areas of the territory. For example Darton (1910, pp. 67–69), building on the observations of 19th century geologists and Shaler (1907) in northwestern New Mexico, described a north-south trending syncline (Gallup syncline) between a Fort Defiance anticline to the west and a large Zuni anticline to the east, which included the Zuni Mountains. Strong upward flexure without faulting of the late Paleozoic and Mesozoic strata along the southwest side of the Zuni Mountains was recognized as responsible for the nearly vertical orientation of these strata in the Nutria and Gallup areas (Fig. 18). To the east Darton described a basin or syncline (Mt. Taylor syncline), which "widens greatly and… merges into a very wide, undulating basin, which extends from the Fort Defiance anticline to the Nacimiento anticline…pitches gradually to the north and holds several thousand feet of Cretaceous and Tertiary strata." Although the name San Juan Basin was not used by Darton or his earlier USGS colleagues around the time of statehood,

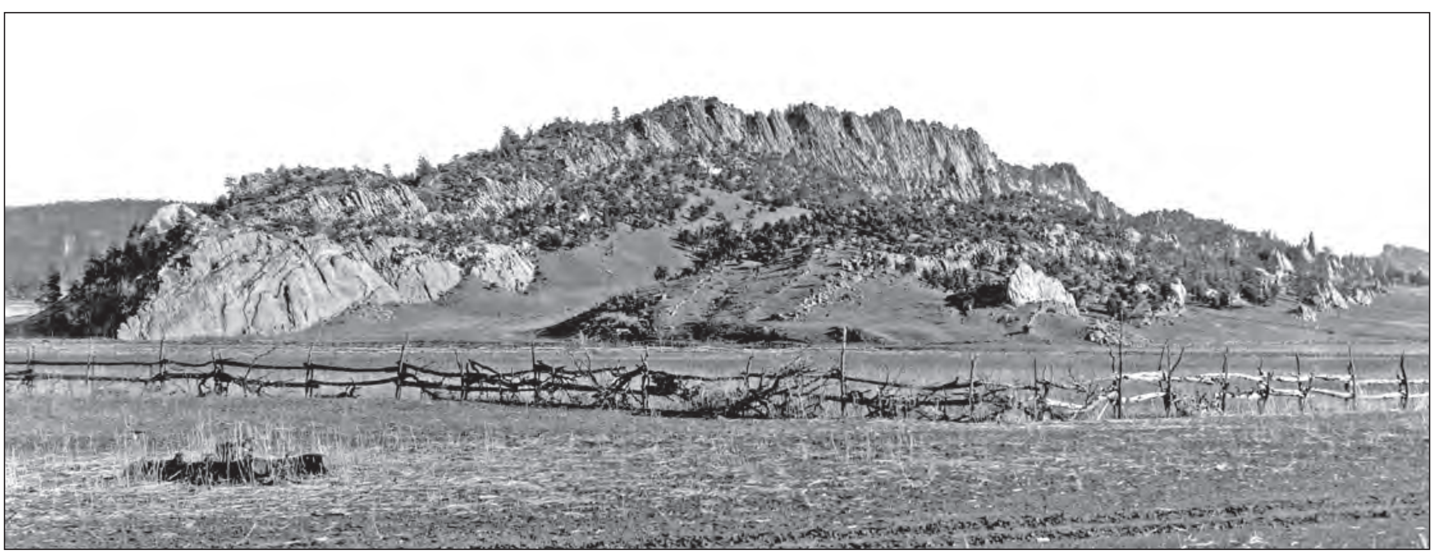

FIGURE 18—Nearly vertical Cretaceous and underlying strata on southwest side of Zuni uplift near Nutria (Darton 1910, pl. 17A), an example of the use of photography in portraying important geologic features in early 20th century USGS reports.

the term was beginning to be employed a few years later (e.g., Bauer 1916). The Nacimiento Mountains, to the east, were interpreted as an anticline with a particularly sharp western margin, where "the strata descend into a deep basin filled with a great thickness of Cretaceous and Tertiary rocks…" The Nacimiento anticline was said to extend southward for some distance without topographic expression, flexed and probably faulted, and to re-emerge as the uplift now known as Mesa Lucero. All of these features were portrayed 40 years later on a structural map of northwestern New Mexico (Kelley 1950).

Outside the "plateau province" (now Colorado Plateau) being studied by the USGS as part of its coal program, other areas of New Mexico were also recognized broadly on the basis of distinctive structure, geologic history, and topography. These included the Great Plains, the Southern Rocky Mountains, and in the southwestern part of the territory structures reflecting G. K. Gilbert's "Great Basin system" (now the Basin and Range province).

In north-central New Mexico, mountain building attained its most dramatic expression, as "tremendous forces" were at work there. Lindgren et al. (1910, p. 25) provided an overview of the structure of this region:

"In the prolongation of the Rocky Mountains of Colorado the sediments were domed and then cut by vertical faults, along which subsidence took place. After erosion these conditions would produce the impression of vertical upthrust of the Pre-Cambrian rocks… South of Glorieta, where the Rocky Mountains proper dip below the Cretaceous sediments, the beds were subjected to stresses which produced monoclinal blocks with more or less pronounced fault scarps. The principal disturbances probably outlined the present valley of the Rio Grande and marked a series of sharply accentuated north-south ranges of apparently tilted blocks, such as the Sandia, Manzano, Oscura, San Andreas [sic], and Organ ranges on the east side and the Nacimiento, Limitar [sic], Magdalena, Cristobal, Caballos, and Cuchillo Negro ranges on the west. Some of the scarps face east, others west. Here also the apparent tilting may be the result of doming, faulting, and subsidence. At the same time was outlined the easternmost chain of the New Mexico ranges, which is separated from the Organ, San Andreas [sic], and Oscura chain by the structural depressions of the Sacramento Valley [Tularosa valley]."

Later, Lindgren et al. (p. 219) stated more directly their view of the structure of the Rio Grande valley, noting that (in central New Mexico) "the Rio Grande appears to follow a great fault zone along the foot of ranges which from Socorro northward face the east, while southward from that point they face the west. The relations of the larger structural valleys are too complex and the data in hand are too insufficient to permit an adequate description. The average width of this great structural trough is nearly 20 miles." The characterization of the Rio Grande and Tularosa valleys as structural depressions or troughs with faulted borders would eventually lead to their recognition as portions of the Rio Grande rift—a major structural feature of New Mexico. We will return to the structure of New Mexico, in the context of geomorphic provinces, in part 4.

Probably the first application of the term "rift" to this feature was in a historically important overview by Vincent Kelley (1952) of what he called the "Rio Grande depression" (Kirk Bryan e.g., 1938, used the same term). Kelley characterized this depression (p. 93) as "a series of north-trending grabens arranged en echelon north-northeasterly along the course of the Rio Grande," described in detail the stratigraphy and structure of each of the constituent basins, and traced its development back to late Miocene time (p. 101). Near the end of his summary he stated (p. 102) that the "depression is a great rift belt," and that its "late Tertiary tectonic pattern is specialized and distinct enough to warrant the application of the term Rio Grande Rift Belt of the Rocky Mountains." Interestingly, however, he believed the grabens did not form by "an east-west release of compression that would allow the simple depression of blocks by gravity alone. Rather it appears that the basins were forced down under compression just as the [bordering] uplifts were forced up."

The synclinal nature of the Jornada del Muerto, in contrast, had been recognized as far back as the 1850s (by G. G. Shumard), and was widely accepted by the early 1900s, although Lindgren et al. (p. 221) expressed reservations, stating that it "is doubtful the structure of the region is as simple as this."

Lindgren et al.'s (1910) description of New Mexico's structural development, although generally accurate, includes some concepts that have been modified by later work. Recall that they believed most mountain building in New Mexico occurred in the early Tertiary, associated with the widespread igneous activity that (we now know) resulted from the Eocene–Oligocene "ignimbrite flareup" that produced many intrusions as well as calderas across New Mexico. The doming that was said to have preceded faulting of these ranges was thought to have been caused by magma intrusions, principally laccolithic. In reality, doming was not a factor, and the faulting that formed these ranges occurred later, mostly after the igneous activity had waned. This also explains why the fault-block ranges mentioned by Lindgren et al. were commonly referred to as monoclines. Intrusions can produce folds, but in present usage monoclines are crustal flexures, commonly around prior subsurface faults, that have both limbs more or less horizontal. Clearly this is not (and never was) the case with the ranges along the Rio Grande, where faulting was the dominant structural control.

Lindgren et al.'s paradigm of mountain building was also applied to the southwestern part of New Mexico. They (1910, p. 26) commented that this region "embraces a part of a province foreign to the [New Mexico] Territory as a whole—that of the Arizona desert ranges, numerous and small, trending northward and separated by desert basins. That these ranges are post-Cretaceous admits of little doubt. Probably they were outlined during the same early Tertiary deformation that produced the ranges of the Rio Grande valley. They differ from the latter by a far less marked monoclinal structure. They were probably outlined by faults. But few of the dislocations are conspicuous in their present topography." The faults bounding most of the small ranges in southwestern New Mexico are indeed not obvious, most being covered by alluvial fans and other erosional debris. Even Darton (1916a, p. 68), working a few years later in Luna County, could only comment that "[possibly] the lowlands [between the ranges] are down-faulted blocks, but there is no evidence for it," and suggested that in general the depressions "are due chiefly to erosion of the softer rocks of the later formations…"

It is worth noting that in the early 20th century there was no clear conceptual separation of the last two major tectonic events in New Mexico's geologic history. The Laramide and "Great Basin" orogenies were beginning to be defined as separate successive events to the north in Utah and Nevada (see Dana 1894, pp. 359–366), but had not been clearly recognized in New Mexico. In Lindgren et al.'s view, mountain building and widespread intrusive igneous processes occupied early Tertiary time, when most of the major structural evolution of the territory had occurred. The subsequent geologic history of New Mexico, and its topographic development, were considered to be influenced mainly by several stages of later volcanic activity, erosion of highlands areas, the filling of intermontane basins with sediments, and reworking of those sediments by fluvial processes.

Likewise, at the time of statehood geologists were unaware of an earlier orogeny of late Paleozoic age. Sedimentation, it was believed, "went on, with some interruptions [from Pennsylvanian time] until the close of the Cretaceous" (Lindgren et al. 1910, p. 25).

However, Lee's work on the "Manzano Group" (Lee and Girty 1909) and subsequent observations led him a few years later to report a widespread unconformity at the base of the "Manzano Group" and equivalent units elsewhere, which marked the regional boundary between the Pennsylvanian and Permian Periods. Lee (1918) went on to suggest that a major uplift, which he called the ancestral Rocky Mountains, was responsible both for the unconformity and the influx of large volumes of eroded, continental, red-bed sediments across formerly marine environments at the beginning of the Permian. By the early 1920s (e.g., Schuchert 1924) the idea of a late Paleozoic episode of mountain building, producing a major uplift extending from Wyoming to New Mexico (ancestral Rocky Mountains), and eroded away by Jurassic time, was well established.

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