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Celebrating New Mexico's Centennial

The geology of New Mexico as understood in 1912: an essay for the centennial of New Mexico statehood Part 4

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Introduction

In this, the final part of this essay on the state of knowledge of New Mexico geology in 1912, I survey the status of geomorphology (then called physiography or physical geography) and the study of surface water (mainly river systems) and groundwater in the new state. Much attention was devoted to managing New Mexico's two largest rivers, the Rio Grande and Pecos, in the years leading up to statehood, and this resulted in several spectacular (for the time) engineering projects directed toward damming these rivers for flood control and to provide water for irrigation. Those on the Pecos River were ultimately largely failures, whereas Elephant Butte Dam across the Rio Grande, begun a few months before statehood as the largest construction project ever attempted in the territory to that time, continues serving its intended functions a century later. Knowledge of Pleistocene lakes, glaciation, and caves was also advancing in 1912. Some concluding comments provide perspective on New Mexico of a century ago and the state of knowledge of the new state's geology.

Geomorphology and water

Introduction

In New Mexico, with its predominantly arid climate, water has always been essential to its human inhabitants. Sources of both surface water and groundwater depend not only on climate but on the landscape and the geologic processes that have molded it. Thus, the results of recent geologic processes, such as the mantle of sediments eroded from highlands and deposited across much of the state during the past few million years, the soils developed upon these sediments, and the work of streams and rivers, past and present, in distributing the sediments, have occupied the attention of geologists in New Mexico from the very beginning of studies in the territory. Space does not allow a full discussion of all studies of Pleistocene to recent sediments and the distribution and use of water in the years leading up to statehood; here only a few major studies and some general trends in thinking and the practical application of such studies are outlined. The reader is referred to John Hawley's (2005) wonderful encyclopedic historical overview of the study of New Mexico's recent landscape evolution, water resources and related subjects, and the ideas driving these studies, for a broader survey of these topics.

Geomorphology

The term "geomorphology," the study of landforms and the processes that produce them, does not appear in any of the geologic literature of territorial New Mexico. Although the term was introduced in 1891 by John Wesley Powell, this subdiscipline of geology, just developing around 1900, was generally referred to as "physical geography" or "physiography," and the latter name was used in textbooks on the subject through the 1940s. But whatever name was used, geologists working in New Mexico in the early 20th century were aware of a variety of surficial processes operating over the past few million years and the strong influence they had in molding present landscapes. They were also familiar with the concept of physiographic (geomorphic) provinces—regions having characteristic topographic features reflecting a more or less unified set of structural, volcanic, and surficial sedimentary processes that shaped an area's modern landcapes, which differ significantly from adjacent areas (see Hawley 2005 for extended discussion).

The concept of physiographic regions or provinces was first fully developed by Powell (1895; see Thornbury 1965 for historical discussion), who published a map of the U.S. divided into physiographic regions. In New Mexico the regions Powell recognized are not much different from those recognized by 1912, or for that matter by modern geomorphologists. The Colorado Plateau, "Basin Ranges," Park Mountains (southern Rocky Mountains), and Arkansas and Pecos Plateau regions (now included in the Great Plains) are all portrayed on Powell's map. Keyes (1906) first specifically discussed New Mexico physiographic regions, dividing the territory into Great Plains, (southern) Rocky Mountains, High Plateau, and Mexican Tableland provinces (Fig. 19). His High Plateau region consisted of the Colorado Plateau, Datil–Mogollon volcanic region southward to Silver City, and the Jemez and Nacimiento Mountains (now considered part of the southern Rocky Mountains). His Mexican Tableland is essentially the New Mexico portion of the Basin and Range, including the Rio Grande rift and Sacramento Mountains sections of modern usage.

Lindgren and Graton (1906; see also Lindgren et al. 1910, pp. 25–26), likewise divided New Mexico into four physiographic provinces, but differed from Keyes in their view of the relationships of the mountain ranges that extend along the Rio Grande. Although recognizing the fault-block origins of the ranges along the Rio Grande valley, they interpreted this "central mountain belt" as a southern extension of the Rocky Mountains. They observed this belt dividing into three lines of uplifts to the south; those along the Rio Grande, a central line including the Sandia–Manzano, San Andres, Organ, and Franklin Mountains, and an eastern uplift that included Sierra Blanca and the Sacramento and Guadalupe Mountains. They also noted (p. 75) that these uplifts "have few features, individually, to distinguish them from many of the desert ranges except in their position as parts of a linear chain of such ranges." In any case, by 1912 New Mexico was generally considered to consist of four physiographic provinces. These provinces, with some

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 has been 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. *New Mexico Geology*, v. 34, nos. 1–4, pp. 1–50; Data Repository 20120001.

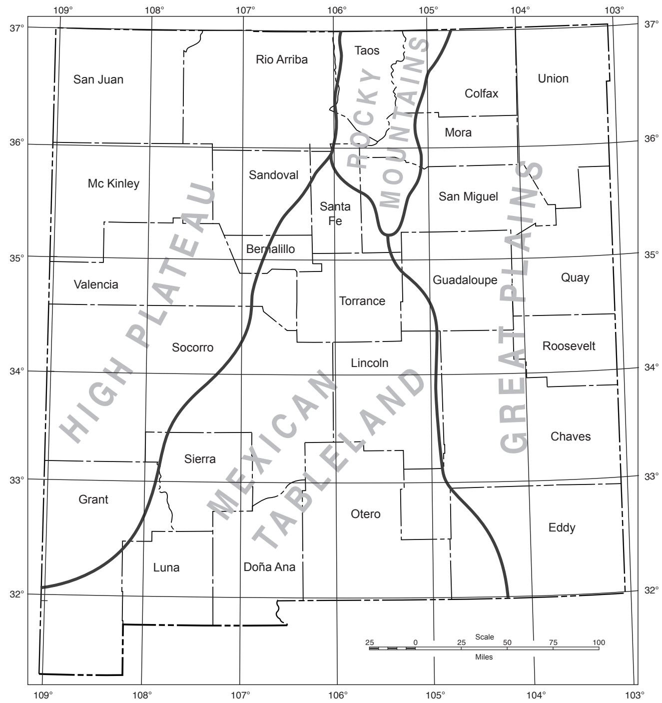

FIGURE 19—New Mexico's physiographic provinces, modified from Keyes (1906).

adjustments and additions, such as a Transition Zone province for the Mogollon–Datil volcanic region (Hawley 2005, fig. 1) and recognition of a Rio Grande Rift section (or province), as well as the subdivision of the major provinces into numerous sections, are still in use today.

Thinking of New Mexico landscapes in terms of geomorphic provinces can be traced back to the work of R. T. Hill, still another USGS geologist. Beginning in the early 1890s (Hill 1891, 1892), and culminating in a USGS folio (1900) and an enormous monograph (Hill 1901), he studied the landscapes and their geologic foundations of Texas, but his work extended westward across the Great Plains into New Mexico as well. He was the first to point out the young lacustrine features of the Tularosa Valley and the very young age of the Carrizozo basalt flows, and, as noted previously, made some perceptive observations of the Raton–Clayton volcanic field. Although his 1900 folio is titled *Physical Geography of the Texas Region*, he devoted much attention to the geology (from basement rock to Phanerozoic stratigraphy) of the regions he investigated, especially in his monograph (Hill 1901). In doing so, he was conceptually changing the emphasis of such studies away from "physical geography" (which recognized regions based mainly on climate, vegetation, and other modern features such as rivers and their drainage) to the deeper geologic framework of modern landscapes that is an essential part of the science of geomorphology today.

The abundant mountain ranges having a variety of different structural origins in New Mexico not surprisingly had attracted much interest by late 19th and early 20th century geologists. Because they are conspicuous landscape features, and many display long and well-exposed rock records representing much of New Mexico's geologic history, and contain many important mineral deposits, early geologists tended to focus their studies on the uplifts within the territory. Yet they also realized that, especially in central and southern New Mexico, the ranges were separated by extensive areas of essentially flat desert plains, and that rivers such as the Rio Grande had modified the landscapes of some of the lower regions of New Mexico significantly. As understanding of fault-block and other uplifts increased, so too did investigations of the complementary troughs, basins, and other depressions that had become filled with thick sequences of sediments eroded from the adjacent highlands. By 1912, based on a few of the deepest wells allowed by available technology, the thickness of some intermontane sedimentary deposits was known to exceed 2,000 feet (e.g., Lindgren et al. 1910, p. 237).

Hill (1900) introduced the concept of bolson plain (bolson means "purse" in Spanish) for a relatively flat sedimentary region formed by the more or less complete filling of an intermontane basin or trough (of whatever origin) with sediments eroded from adjacent highlands. Bolsons are largely structural in origin, floored with unconsolidated sediments, and their margins are commonly characterized by talus hills, fans, and stream-derived detritus, whereas lake deposits may occupy the interior parts of these plains. Thus bolson plains are a record of later topographic development than are plateaus, which typically have the same stratigraphy as neighboring uplifts, but precede the effects of more or less modern rivers, which produce and distribute more recent sedimentary deposits.

Tight (1905) elaborated on Hill's concept of bolson plains with special reference to New Mexico, partly in response to an earlier paper by Keyes (1904) misapplying the concept to high, bedrock-floored plateaus such as the Llano Estacado and his idea that bolson plains were uplifted peneplain surfaces not yet affected by river erosion. As an aside, this exchange was an interesting example of the geologist-presidents of the University of New Mexico (UNM) and the New Mexico School of Mines arguing in the literature about New Mexico geology. The Hill/Tight view of bolsons prevailed, and Lindgren et al. (1910, pp. 221–222) went on to describe some of these filled-trough structures, and the sloping alluvial fans, drainage patterns, and other features that characterize the bases of many arid mountain ranges in New Mexico.

The action of rivers, particularly the Rio Grande, and especially the sediments and floodplains associated with them formed a part of many regional geologic studies in territorial New Mexico. Aside from the importance of river discharge and sediment distribution in agriculture (see below), ancient river sediments indicating changes in course, downcutting (at least 300 feet from former levels in some places), terraces, and fluctuations in sediment load and grain size were at least observed, if not thoroughly studied by early 20th century geologists in New Mexico. Detailed, more modern studies of the rich variety of fluvial and related facies in the Rio Grande valley, as well as climate and tectonic influences on the river, lay in the future (and were led by territorial UNM alumnus Kirk Bryan, e.g., 1938).

By the first decade of the 20th century, however, early students of the Rio Grande were beginning to speculate on the history of the river. Recognition of the very recent ages of some basalt flows near the Rio Grande led to suggestions that these eruptions had changed the course of the river. For example, Lee (1907b), based on his study of the Rio Grande valley and the relationships of volcanic rocks with river and tributary sediments, recognized three geologically recent volcanic episodes that may have affected the course of the river in the past. From oldest to youngest, these are the Jemez and Socorro volcanics, the Albuquerque and Cerro del Rio volcanics, and the Jornada basalt flow and smaller flows on the La Mesa surface in Doña Ana County. Such authors as Tight (1905) and Lee (1907b, c) discussed evidence that the Rio Grande had formerly flowed east of the Caballo Mountains through the Jornada del Muerto at one time. Lee believed that the river had been deflected to its present course by the outpouring of the San Marcial (Jornada) basalt flow.

Ideas concerning the age of the Rio Grande as a through-flowing river were inhibited by the lack of precise dating techniques. Even so, Lee (1907b, c) strongly advocated that the Rio Grande once had flowed southward into Mexico across the La Mesa surface west of Cerro de Cristo Rey and was deflected to its present course at El Paso either after its valley floor had aggraded to the level of El Paso canyon, or, as Hill had suggested, the Rio Grande was captured by headward erosion from the south, by a separate river flowing into the Gulf of Mexico, which then became the lower portion of the Rio Grande as we know it today. Even following the advent of more modern studies of the river, the question was argued by many authors. Recent thinking (Connell et al. 2005, pp. 135–136) suggests that the river became through-flowing through the basins of New Mexico by about 4 million years ago, and for much of the Pliocene terminated in a system of interconnected playa lakes named Lake Cabeza de Vaca in southern New Mexico and northern Chihuahua. Connection with the Texas–Mexico boundary portion of the Rio Grande was established in late Pliocene time (Connell et al. 2005, fig. 10).

Less attention had been devoted to the geomorphology of other river systems in the territory, but one of the first extensive geomorphologic studies of any part of New Mexico (published in the *Journal of Geography,* as was customary at the time) was Lee's (1903) study of the geomorphology of the Dry Cimarron and Canadian Rivers and their tributaries in northeastern New Mexico. This study was firmly based in the geology of the area. Lee showed the influence of different sedimentary and volcanic units on the incision of the river valleys and canyons, documented changes in gradient along the streams, described stream and canyon sediments and their source rocks, the formation of headlands and isolated buttes in the wider valleys as a result of shifts in the channels of the main and tributary streams, and the reciprocal effects of lava flows, erosion, and fluvial sedimentation, recognizing for example that the flows on the higher mesas were older than flows in eroded areas. Lee also speculated on the evolution of the modern drainage system, and calculated that 947 cubic miles of sediment had been removed from the Canadian River valley alone through time. The approach is not just descriptive but strongly process oriented, and in that sense distinctly modern. Lee published it while in graduate school, and it probably helped him to get hired by the USGS a short time later.

Surface water

New Mexico's rivers have long influenced erosion, sediment deposition, and modification of landscapes across the state, and the Rio Grande and Pecos River in particular have been historically important as focal areas for settlement and agriculture. Settlement along the Rio Grande began long before the Spanish arrived in the 1500s, and when American administration began in 1846 virtually the entire population of the territory, except for the western pueblos (Acoma, Laguna, Zuni), lived within proximity to the river. Use of groundwater, on the other hand, only began in New Mexico with the development of artesian wells in the Roswell area in the early 1890s. By 1912, although more artesian wells, additional shallow wells along the Rio Grande floodplain, and some spring water had been developed, streams and rivers still provided by far the greatest volume of water used by New Mexicans.

Irrigation projects to increase agricultural productivity were commonplace in many parts of late territorial New Mexico, and varied from small local efforts to grandiose projects managed by large private companies or the federal government's Reclamation Service. In addition, diversion of surface water had been used for mining, for example the construction of the "Big Ditch" in the late 1860s to carry water from the Red River to the Moreno Valley to wash placer deposits near Elizabethtown. Benjamin Silliman (1880) studied in some detail the fluvial geomorphology and gold content of the river gravels of the northern Rio Grande, and proposed a large-scale diversion of Rio Grande water through canals and pipes from north of the Red River, 40 miles across the western mesa, to Embudo, for use in the hydraulic mining of the river gravels there. Here, we will focus on several attempts to vastly increase use of Rio Grande and Pecos River water for irrigation and settlement.

Flow of the Rio Grande through the 19th and early 20th centuries was unpredictably variable, with serious to devastating floods in some years (e.g., 1874, 1884, 1891, 1903, 1909, 1912; see Kelley 1982) and diminished flow during droughts (especially 1893–1902) that adversely affected agricultural productivity. Attention to the supply of water in the Rio Grande, important to communities and farmers near the river for centuries, also began to be addressed by the newly formed USGS in the 1880s. Its second director, John Wesley Powell (1881–1894), had a deep interest in the larger subject of water in the arid western U.S., and strongly influenced the survey's role in defining and managing the region's water supplies. The USGS's long-running series of Water-Supply Papers, begun in the 1890s, reflected this mission.

In addition, the first stream-gaging station in the western U.S., which also served as a training center for USGS hydrologists, was established along the Rio Grande near Embudo, north of Española, in 1889. Hawley (pers. comm., 2011) noted that "the first engineer-in-charge of 'Camp Embudo' was Frederick H. Newell, who has been referred to as the 'father of systematic stream gaging' in the USA. He was subsequently appointed as the first director of the U.S. Reclamation Service when it was separated from the USGS in 1907 (Frazier and Heckler 1972; Hawley and Kernodle 2008)." The Embudo gaging station is still operating today. One of the "student-hydrographers" at Camp Embudo, Ralph F. Tarr, wrote the first paper dealing specifically with drainage systems of New Mexico, particularly of the northern Rio Grande (Tarr 1890). Tarr viewed the present Rio Grande and its tributaries as a young drainage system, superimposed upon geologically young volcanic rocks but generally following an older drainage system established with uplift of the southern Rocky Mountains.

New Mexicans living along the Rio Grande had been managing the flow of the river in a minor way by constructing acequias that diverted water into ditches and small canals for agricultural purposes. In some years, especially during droughts, upstream farmers in northern New Mexico and Colorado diverted enough water to adversely affect amounts available to farmers in the southern part of the territory (Mesilla Valley) and around El Paso, Texas. As early as the late 1880s plans were prepared to construct a dam a few miles north of El Paso that was believed to be needed to equitably distribute Rio Grande water in the southern areas, and to Mexico. In addition, however, in 1893 the Rio Grande Dam and Irrigation Company was chartered by the U.S. Department of the Interior to build a private dam on the Rio Grande near the town of Engle, far upstream of El Paso (see Coan 1925; Mueller 1986). The two plans were mutually contradictory; an El Paso dam would deprive southern New Mexico of irrigation water, whereas the proposed Engle dam could cut off most of the water to the south, especially to El Paso, and had international implications in that Mexico might be deprived of its fair share of Rio Grande water. Lawsuits and much deliberation by the federal government ensued, while (1904) the private irrigation company went bankrupt. It was during these unsettled times when USGS geologists were sent to study and evaluate water conditions along the central and southern Rio Grande.

Willis Lee, who had joined the USGS in 1903 as an assistant to N. H. Darton, was transferred from Arizona to New Mexico and spent the 1904 and 1905 field seasons studying the water resources of the Rio Grande valley, from Santa Fe to the Texas state line. In the resulting report, Lee (1907b) described the sediments, geomorphology, and bedrock geology of the lands in and around the Rio Grande valley, as well as the valleys and canyons through which the river flowed, and the subsidiary drainages that fed the river. He assembled detailed records of evaporation, rainfall, and river discharge, and well records documenting the underground waters. Lee (pp. 26–30) also evaluated the suitability of several locations for a dam across the Rio Grande, including the type and strength of the bedrock that would support a dam as well as the sedimentary characteristics of adjacent valleys that would contain the reservoir waters backed up by the dam. Of five possible sites (El Paso Canyon, Engle, San Acacia, San Felipe, White Rock Canyon) Lee devoted most attention and gave his strongest support to the Engle site (Fig. 20), "in a rock canyon near Elephant Butte" (p. 26).

Presumably based on the results of Lee's work (before it was published) as well as other studies, the U.S. Congress in 1905 formally authorized Elephant Butte Dam, concluded a treaty with Mexico for the delivery of 60,000 acre-feet of Rio Grande water each year (1906), and provided an initial ($1 million) appropriation

FIGURE 20—Proposed "Engle dam site" along Rio Grande, with Elephant Butte at right (Lee 1907b, pl. 9).

for construction (1907). Smaller diversion dams and canals, such as Leasburg Dam, were completed first (1908) in order to divert Rio Grande waters for the irrigation of the north end of the Mesilla Valley (Coan 1925). After some delays preliminary planning for Elephant Butte Dam was completed in July 1911, and construction began later that year. It was by far the largest construction project New Mexico had ever experienced, as well as the most expensive—total cost was $5.115 million, rising to $7.2 million if related canals and diversion channels are included—and construction lasted four years before the dam was completed in May 1916. Economically, dam construction represented an input of federal funds into New Mexico that yearly was roughly equal to one-half of the total annual budget of the new state.

The dam is anchored on resistant sandstone of the Late Cretaceous Mesaverde Group and is composed of blocks of Mesaverde sandstone embedded in a concrete matrix. It is nearly 1,700 feet wide (including the spillway), 306 feet high, and had a design storage capacity of 2.6 million acre-feet of water (Mueller 1986), sufficient for the irrigation of 155,000 acres in New Mexico and Texas. At the time it was the largest dam in the U.S. and of course is still serving its intended functions a century after construction began.

Along the Pecos River in southeastern New Mexico, ranching began to give way to farming in the 1880s. In order to expand farming and attract new settlers to this arid region, irrigation was required, and by 1887, Pat Garrett (of Billy-the-Kid fame) and the Eddy brothers, early cattle ranchers and large land owners in the Pecos country, had begun to divert water from the Pecos River into irrigation ditches. Various federal acts allowed irrigation companies to secure rights of way and tax exemptions for building dams and canals, and therefore to develop agriculture on a large scale (Reeve 1961, p. 247). What followed was the largest (except for the creation of the railroad network), privately funded civil engineering project in the history of territorial New Mexico. Initially successful, the program was ultimately defeated by mother nature and a national economic depression, and the federal government took it over in 1905. Space does not allow more than a brief summary here, but the full story is told in great and fascinating detail by Hufstetler and Johnson (1993).

In 1888 the Eddys and several other investors, including J. J. Hagerman, incorporated the Pecos Irrigation and Investment Company to manage the development of Pecos Valley irrigation projects, and expanded the construction of irrigation canals. An influx of settlers led to the platting of a townsite (named Eddy, which later became Carlsbad) that same year, and in 1889 to the creation of Eddy County. Ralph Tarr, of the USGS's Reclamation Service, visited in March 1889 and reported completion of a 40-mile canal in the Roswell area and plans for constructing a system of canals and a dam farther south, that would provide irrigation for 125,000 acres. By 1890 the dam across the Pecos had been completed (Avalon Dam), backing up a reservoir 7 miles long and 1.5 miles wide, and feeding a substantial network of canals. Avalon Dam was a rockfill structure aproximately 1,070 feet wide and 45 feet high and was reputed to be the largest irrigation dam in the country at the time. That same year the Pecos company was reorganized to allow it to buy thousands of acres of land around the canal network (for future lucrative sales to newcomers), and Hagerman built a railroad from Pecos, Texas, to Eddy to connect to a transcontinental railroad that would allow easy access of Pecos agricultural products to markets across the country. Prospective farmers, wine growers, and investors poured into the Pecos Valley.

W. C. Cummins, a geologist with the Texas Geological Survey, visited in 1891 and wrote a report (Cummins 1892) that described what had been accomplished so far: two long canals paralleling the Pecos River from Roswell southward; Avalon Dam 6 miles north of Eddy, smaller canals south of the dam, another large canal (named for Hagerman) diverting water from the Pecos approximately 15 miles south of Eddy, and additional dams and irrigation canals being built along the river in Texas, just south of the New Mexico state line. This was irrigation engineering on a massive scale, especially for a remote, arid, and economically rather backward territory. A second dam, McMillan, was completed in early 1893, 9 miles north of Avalon Dam, its larger reservoir providing much additional water storage for supplying the irrigation canals. This was another rockfill dam, nearly 1,700 feet wide and as much as 55 feet high.

The dams and canals, however, were proving to be far less efficient than their builders had anticipated. Seepage from the reservoirs and canals into the evaporitic, sinkhole-pocked Permian bedrock was considerable. In addition, there were other looming problems. Cummins (1892), although positive about the long-term viability of the Pecos Valley for large-scale irrigation and agriculture, also studied the local geology and tested the waters of the Pecos and its local tributaries. He warned (pp. 220–221) that the river water is alkaline and "carries salt, which if not removed by flooding or draining, will in time so impregnate the soils that they will lose their present fertility." It is worth noting that there is little evidence to suggest that the geologic environment across which this large engineering undertaking was spreading was studied or seriously considered.

All of these ambitious plans to turn the Pecos Valley into rich, agriculturally productive lands were washed away in August 1893, when a devastating flood, the worst in historical times, swept down the Pecos River, destroying Avalon Dam, and seriously damaging McMillan Dam and the other major structures of the irrigation system, as well as the railroad. Moreover, the depression initiated by the Panic of 1893 precluded the large amounts of additional outside investment needed to repair the system. Hagerman committed much of his remaining capital to restoring the infrastructure of the irrigation system and much was accomplished by 1894, but it was ultimately a losing battle. The waterlogged alkaline soil, marginal for many types of crops to begin with, deteriorated as gypsum and other salts were deposited. The economic depression wiped out many of the farmers, who drifted away.

The irrigation company's canals continued to function through the rest of the 1890s, but agricultural activity was a shadow of what it had been, and the company lost money. The territorial government continued to work with the company in promoting Pecos Valley land throughout the country, through its "Bureau of Immigration" (one brochure showcased the Pecos Valley as "the fruit belt of New Mexico"). Experimentation in growing a variety of crops continued but with little success. Finally, the Pecos Irrigation and Improvement Company went into receivership in 1898, reorganized as a new corporate entity, and was marginally profitable through the early years of the 20th century, as successful crops of cotton were established, and a new railroad connected the region northward with Midwestern markets. However, in 1901 only about 9,000 acres were being irrigated—a far cry from the 100,000 or 200,000 acres projected during the overly optimistic early stages of the project—and expensive repairs to the infrastructure were a continuing drain on resources. Then, in October 1904, after two years of drought, the Pecos River suffered another devastating flood, which severely damaged the two dams and much of the canal system, rendering it inoperable, and leaving the farmers without water for their next season's crops.

The irrigation company and landowners had little financial resources left, but began to rebuild while at the same time appealing to the federal Reclamation Service, at that time a division of the USGS, to take over the irrigation system. The Reclamation Service (later to be detached from the USGS and in 1923 renamed the Bureau of Reclamation) was established in 1902 by new president Theodore Roosevelt and reflected a major change in the previously laissez-faire policies of the federal government, which had allowed land promoters and other private concerns to largely control the distribution of water in the West, as in the Pecos Valley. The Reclamation Service sent engineers and geologists to examine the situation, and its personnel coordinated a temporary rebuilding effort, using local funds. Avalon Dam was repaired but immediately failed again, dooming the farmers to a dry 1905 growing season. Surveyors, mappers, geologists, and engineers continued to study the dam sites and other irrigation facilities through 1905, made reports (mostly unpublished; more thorough studies of the geology and water of the Pecos region were conducted in the years following statehood), and ultimately recommended a federal takeover the facilities. This was accomplished by the end of 1905. For $150,000 the Reclamation Service acquired all of the components of the irrigation system into which the private companies had invested more than $2 million over the previous 15+ years.

Rehabilitation of all of the irrigation facilities progressed through 1906, and most work was completed by early 1907 (McMillan Dam was renovated in 1908–1909). At the same time federal soil scientists studied soil quality and prospective agricultural practices to determine which areas would be best served by the new irrigation system—studies that had been conspicuously absent during the era of private management (one exception is a study of irrigible floodplain areas of the Pecos River by Means and Gardner 1900). The transition to government control did not go smoothly, as there were new restrictions on land ownership and fees were assessed not only for the water being supplied but also to eventually repay the government for its investment in the repairs. Complaints that the "Carlsbad Project," as it was now called, was not irrigating as extensively as it could were also common, especially among large landowners. These issues, and additional repairs because of flooding in 1911, continued as New Mexico transitioned to statehood, and further studies, expansions, and other work on the irrigation system occupied the Reclamation Service for several more decades. The construction of Alamogordo Dam and Reservoir north of Fort Sumner in 1937 removed the danger of severe flooding and formed the main storage unit for Pecos River water that would be used far downstream in the Carlsbad area. Control of the irrigation facilities was finally transferred from the Bureau of Reclamation to local authorities of the Carlsbad Irrigation District in 1949.

By the time New Mexico became a state then, an ambitious large private irrigation company had been established to utilize Pecos River water, but had not met expectations, and eventually had failed, to be taken over by the federal government, which was engaged in rebuilding the irrigation facilities and expanding irrigated land. At the same time, the federal government had embarked upon a much larger civil engineering project to manage the waters of the Rio Grande in the southern part of the state. Other smaller irrigation projects around New Mexico were also being attended to by the federal Reclamation Service. Despite the difficulties of the Pecos irrigation program, the area of the territory that was served by irrigation for agricultural purposes had increased greatly in the years leading up to statehood. By one account (Statesman's Yearbook 1913) irrigated land in New Mexico increased from 204,000 acres in 1900 to 750,000 acres in 1911. The number of farms increased 176% from 1890 to 1900, and increased by another 190% from 1900 to 1910 (Reeve 1961). Agriculture, assisted by geologic, hydrologic, and engineering studies, was becoming an important element of the new state's economy.

In the decades following New Mexico statehood many new dams and reservoirs, from small to large, were constructed all over the state. Some were built by federal agencies, others by the state or local irrigation districts, but most were designed to store water for irrigation and flood control. Some are now state parks, where recreation is an important additional function. Today, surface water still accounts for about 57% of New Mexico's total water use (Stone 2001), with the remainder derived from groundwater, a resource that has largely been developed since statehood was attained. About 95% of all surface water is currently used for agricultural purposes, and agriculture accounts for about 75% of all New Mexico water consumed. Domestic use of water in New Mexico, mainly in urban areas, though relatively small, is derived almost entirely from groundwater.

Groundwater

Study of groundwater in New Mexico began very modestly in the last years of the 19th century, with local reconnaissance reports that included "subsurface water" use in evaluations of irrigation potential in places like the Mesilla Valley (e.g., Barker 1898), and initial regional observations of artesian and other underground waters in parts of New Mexico (e.g., Hill 1893) The first compilation of information on water resources of the Rio Grande basin (Follansbee et al. 1915), while dealing mainly with surface water, also included data on the seepage of water into and out of streams (see Hawley and Kernodle 2008 for an overview of early hydrologic research in New Mexico).

At the time New Mexico became a state, dozens of springs producing both cold and hot (see Summers 1976) waters were known around New Mexico, and some fed small lakes and streams. A few of these produced sufficient water to be used locally for

FIGURE 21—Artesian well, near Dexter, south of Roswell (Fisher 1906, pl. 7).

small-scale irrigation, and some hot springs were used by bathers for their supposed curative qualities, and some spring water was even bottled and sold for medicinal purposes. Use of groundwater on a larger scale began near Roswell in 1891, with the sinking of the first artesian wells, in which water pressure at depth is sufficient to send the water up a well to the surface (Fig. 21). Fisher (1906) provided an early study for the USGS on the artesian waters along the Pecos River, from Roswell nearly to Carlsbad, at which time around 250 wells were operating. Fisher's detailed examination of well log records showed that depth to water varied between locations, averaging 250 feet near Roswell, and ranging from 300 to 1,000 feet around Hagerman, and 800 to 1,000 feet near Artesia. The main subsurface source of this water was believed to be an unnamed late Paleozoic limestone directly beneath Permian red beds. Fisher explained (1906, p. 23) the origin of these waters as follows:

"The water-bearing formations in the Roswell artesian area outcrop in successive zones on the higher slopes to the west. There they receive their water supply by direct absorption of rainfall and sinking of streams. These streams all rise high on the slopes of the Capitan, Sierra Blanca, and Sacramento Mountains, where the rainfall is relatively large. As a result they carry an abundance of waters in their upper courses, all of which sinks in the outcrop zone of the porous limestones and the overlying formations and passes underground to the east. After the water has entered these porous formations it is confined by impervious layers of limestone or clay, and under the lower lands to the east it is under considerable pressure."

These artesian waters were mainly used for agricultural irrigation and domestic purposes. More than 1,400 artesian wells were operating in the Roswell area by 1926, with a predictable decline in volume of water produced. Many of the wells went dry, as did streams and springs in the area (Howard 1993).

Elsewhere in New Mexico, along the central and southern stretches of the Rio Grande shallow wells near or on floodplain sediments produced water, but pumps were required to get it to the surface. The first detailed study of groundwater in the vicinity of the Rio Grande was conducted in 1904 by Slichter (1905), as a response to shortages in Rio Grande flow because of a recent drought. Slichter studied existing wells in the El Paso area and in the Mesilla Valley, several sunk by the Agricultural College, and established two additional lines of shallow wells across the valley. His analyses of these wells included depth to the water table, and changes in discharge and depth to water during pump tests, leading to a simple model of groundwater underflow in the valley. He also analyzed the costs of pumping water using engines that ran on various fuels such as gasoline, crude oil, wood, and electricity. A major flood along the Rio Grande in October 1904 allowed him to ascertain its effects on the wells, leading unsurprisingly to the conclusion that the river was the main source for the underground water in the region, with relatively little coming from the highlands outside the river valley.

Lee's (1907b) study of water resources along the central and southern Rio Grande in New Mexico also included groundwater, and he provided information on the wells, mostly developed on or near floodplain sediments close to the river. Few successful deep wells were reported. Generally the well water was pumped from unconsolidated Quaternary fluvial and valley-fill sediments. At this time there were apparently no major coordinated or concerted efforts to develop underground water resources. Wells were constructed in some cases by city waterworks (as in Albuquerque and El Paso), by individuals (often ranchers requiring water for their stock), by institutions like the Agricultural College in Las Cruces, and by the railroad companies, which needed sources of water at sidings to replenish their steam locomotives. As New Mexico approached statehood, though, there was an increasing understanding that use of groundwater had great potential to augment the supplies of surface water, especially during droughts, for irrigation and for domestic uses.

The most comprehensive study of water resources in any area of New Mexico in the early 20th century was mostly completed in 1911 and 1912 by O. E. Meinzer (USGS) and R. F. Hare (New Mexico Agricultural College), but not published until 1915. Most of the information was from Meinzer's work; Hare did the water analyses. This study concerned the Tularosa Valley, a sparsely populated area of approximately 6,000 square miles, and is one of the classic works on New Mexico geology.

Meinzer and Hare examined every natural feature of the valley that conceivably had any relationship to its water resources. They first discussed the physiography and drainage of the region, moving on to thorough descriptions of each rock unit exposed (augmented by subsurface well data), and devoting considerable attention to younger geologic features of the Tertiary(?) to Quaternary "valley fill," including depositional processes, arroyo incision, and the origin of large "alkali flat" gypsum deposits around White Sands. The White Sands dune field (Fig. 22) and Carrizozo basalt flows were studied in fair detail. For the latter, the absence of significant weathering, soil development, vegetation, and stream erosion, and only minor recent sediment deposition and arroyo cutting along the margins of the flow led them to the conclusion that "the younger flow" [the two flows of the Carrizozo basalt field] was "at least several hundred years, but in all probability not more than a few thousand years" old (the actual age is about 5,500 years). They also recognized "great fault scarps" along the east and west sides of the San Andres and Sacramento Mountains, respectively, and followed Herrick (1904a) in interpreting the valley as the central part of a great arch that collapsed along the faults, dropped, and is now buried beneath a thick sequence of relatively young sediments.

Meinzer and Hare also assembled climate records influencing water availability and discussed the relationships and interactions between surface and groundwater. Both surface water, which provided most of the irrigation water in the valley and emanated from streams and springs in the Sacramento Mountains, and groundwater were thoroughly documented. They provided a detailed catalog of information of all wells, including well logs, depth to water figures, water quality data, and suitability for drinking and other purposes (e.g., use in boilers and toilets), and the wells were grouped by the subsurface strata (Carboniferous, Cretaceous, and "valley fill") that provided the water to them. Their treatment of wells extended to analyses of different types of pumps, proper

FIGURE 22—The edge of the White Sands gypsum dune field, studied by Meinzer and Hare (1915, pl. 12).

surface irrigation procedures, and the qualities to be incorporated in effective reservoirs. More than 30 pages of their more than 300-page-long report were devoted to a detailed account of sources of water available to travelers along railroads and wagon roads through and leading out of the valley. Perhaps most remarkably, Meinzer and Hare examined the types of soil developed in various areas of the valley, and studied the relationships of these soils to bedrock, water circulation, depth to water table, and "plant food" (nutrients) available. Soil geochemistry was analyzed, as was the distribution of native vegetation relative to bedrock geology, soil types, temperature, and water availability.

More could be said about this remarkable study, but suffice it to say that it represented not only the most comprehensive water-related study to come out of territorial New Mexico, but one of the most innovative studies done anywhere in the U.S. in the early 20th century. The vast amount of practical information in it must have been of great value to settlers and local land managers, but it also charted new scientific avenues for hydrogeologic studies as well. It is widely recognized as a landmark in the study of arid-region hydrogeology and has been widely used and cited through subsequent decades to the present. Moreover, the Tularosa Valley investigation complemented Meinzer's (1911) seminal study of the geology and groundwater resources of the Estancia Valley, which included the first detailed description of a Pleistocene pluvial-lake system in this part of the American West (see following section).

Meinzer completed other studies in New Mexico and many outside the state as well. During his 40 years with the USGS (1906–1946), 34 of them as chief of its groundwater division, Meinzer's influence on the discipline of groundwater hydrology was enormous, to the extent that he is widely regarded as the "father of modern groundwater hydrology" (Hackett 1964). He emphasized aquifers as functional components of the entire hydrologic cycle (Fig. 23), advocated

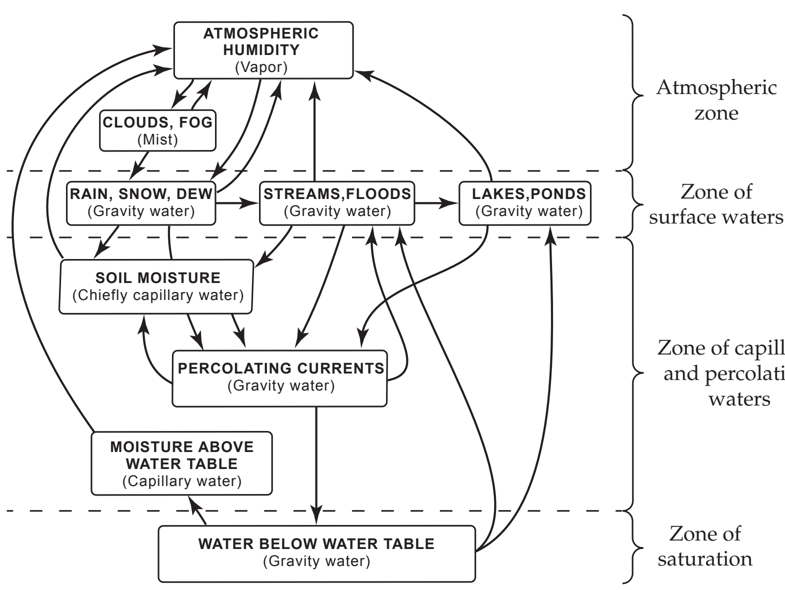

FIGURE 23—Meinzer's concept of the interrelationships between surface and groundwater within the hydrologic cycle (redrawn from Meinzer and Hare 1915, fig. 26).

an interdisciplinary approach (involving geologists, chemists, engineers, and physicists) to the study of groundwater, and established many of the terms and concepts now routinely used in hydrogeology (see Hackett 1964; Stringfield 1974; Maxey 1979; and Hawley and Kernodle 2008 for more information). His influence on this discipline is reflected by the fact that the most prestigious award in hydrogeology conferred by the Geological Society of America each year is the Oscar E. Meinzer award.

Pleistocene lakes and glaciers, and caves

As New Mexico became a state, geologists were well aware that the cooler, moister climates of the Pleistocene had produced large pluvial lakes in the now-arid basins of the West. Recognized first in Utah (e.g., Lake Bonneville) in the early 1880s, Pleistocene lakes were beginning to be documented in New Mexico in the first years of the 20th century. Herrick (1904b; see also Lucas and Hawley 2002) described lacustrine sediments that indicated the presence of a large lake, which he named Lake Otero (Fig. 24), across much of the Tularosa Valley, although he believed it to be a salt lake of Tertiary age. Meinzer and Hare (1915), in their comprehensive study of the Tularosa Valley, gave cautious support to the concept of Lake Otero, but believed that the main evidence of a Quaternary salt lake was the extensive areas of gypsum flats, deposited when the lake water evaporated, rather than geomorphic features such as lake terraces, most of which they interpreted as fault scarps (pp. 42–46).

The evidence for a Pleistocene lake in the Estancia Basin was more compelling. Meinzer (1911), in a characteristically comprehensive study of the geology and water resources of that basin, recognized cliffs, terraces, beaches, beach ridges, spits, and bars at various locations around the margins of the "valley-fill" sediments of the basin, and estimated the extent of the lake as 450 square miles in area and 150 feet deep. Meinzer noted that the lake had developed in the "cold, humid, glacial climate" of the Pleistocene but because he could find no likely outlet he interpreted Lake Estancia as a large salt lake, now reduced to sand dunes and many small playa lakes. Earlier Johnson (1902) had studied these lakes, the sands around them, and the chemistry of their waters, but had made no suggestion that they were remnants of a larger Pleistocene lake. As many as 11 permanent late Pleistocene pluvial lakes are now known to have existed in New Mexico (see Hawley 1993; Allen 2005 for more information).

The existence of Pleistocene glaciers in the high mountains of New Mexico was also well documented 100 years ago. Salisbury (1901), for example, studied the evidence for glaciers in the Truchas Peaks–Pecos Baldy area north of Santa Fe. He noted about 50 cirques separated by ridges bearing serrated crests, striated and polished rock surfaces, and moraines stretching 7 miles down the valley of Santa Fe Creek to an elevation of 9,200 feet. He concluded (p. 728) that elevations of "11,700 to 12,000 feet seems to have been necessary for the generation of glaciers." Unknown at the time were the small moraines produced by glaciers on Sierra Blanca (elevation 12,003 feet), far to the south, near Alamogordo—the southernmost mountain glaciers in the continental U.S.

The most spectacular result of the action of underground water in New Mexico—the creation of Carlsbad Caverns—was scarcely known in 1912, except for the marginally economic bat guano that was mined from it beginning in 1903. A few local people had explored some distance beyond the entrance and the first photos were taken in 1908 or 1909, but wider knowledge of the caverns and the first trickle of tourists did not appear until the late 'teens (Nymeyer and Halliday 1991). Willis Lee first descended into the caverns early in 1923, was amazed, and immediately began to publicize it among various influential groups, including the National Geographic Society, which funded the first real scientific exploring expedition in 1924. Lee extensively photographed within the caverns and took a leave of absence from the USGS to become the custodian of Carlsbad Caverns when it was designated a national monument in October 1923. The monument became New Mexico's first (and only) national park in 1930.

Concluding comments

The first decade of the 20th century, leading up to the territory of New Mexico becoming the 47th state in 1912, was a time of rapid social and technological transition. The more than 300,000 New Mexicans were becoming familiar with many innovations that would mature to become essential parts of 20th-century life in the decades to follow—transportation by autos and airplanes; instant communication via telephones and radio; capture of sound and images by phonograph records, moving pictures, and inexpensive box cameras that anyone could operate; and such conveniences in homes as indoor plumbing and electric lights, to mention a few. Yet

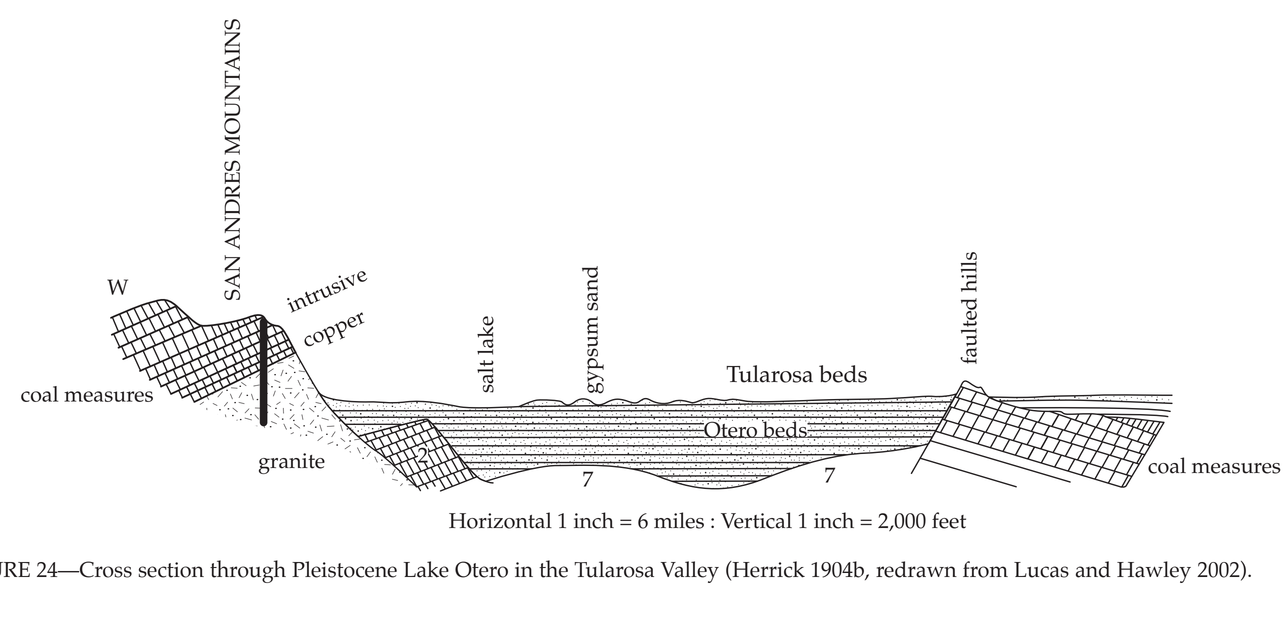

FIGURE 24—Cross section through Pleistocene Lake Otero in the Tularosa Valley (Herrick 1904b, redrawn from Lucas and Hawley 2002).

individual lives were considerably shorter, on average, than today, and manual labor, especially in such important areas as ranching, farming, and mining, was far more intensive in the slower-paced lives of most late-territorial New Mexicans. One can argue whether the quality of living has increased or decreased over the past century, but what is certain is that New Mexicans at the time of statehood had access to only rudimentary medical knowledge and health care, had little knowledge of dangerous pollutants in their food and drink, and few had any understanding of or interest in the effects of human activities on the larger environment around them. Moreover, people lived generally a much more precarious existence economically; wages for most jobs were low, barely what was needed to get by, and the loss of one's job was not buffered by any form of government unemployment support or social security or pension plans. More than one-half of the adult population of New Mexico (women and Native Americans) were disenfranchised and therefore had no direct influence on the laws that governed them or choice of the men who created these laws.

Knowledge of the geology of New Mexico in the decade before statehood advanced at an unprecedented rate, far more than in any preceding decade and possibly more than in any subsequent decade as well. Courses in geology were offered at two institutions, the University of New Mexico and the New Mexico School of Mines, and the presidents of those universities conducted research, published upon the geology of the territory, and trained a few students who would go on to become noted geologists.

Of much greater significance, however, was the entrance, in force, of the USGS into the territory during the decade before statehood. Survey geologists transformed contemporary understanding of most aspects of New Mexico geology. Before 1900, for example, sedimentary strata in New Mexico were known only generally, with little to no information available for many areas. By 1912, a detailed stratigraphy, with dozens of named formations and accurate geologic ages, had been established for Paleozoic, Mesozoic, and to a lesser extent Cenozoic sequences around the state. Significant advances also occurred in documenting the relative ages and structures of volcanic rocks, the nature and composition of intrusive igneous bodies and the state's Precambrian rocks, and in understanding in much greater detail the structure, Quaternary geology, and surface and subsurface water resources of the state. Knowledge of the geologic occurrences of New Mexico's metal and coal resources also increased considerably during this time. Only in the realm of vertebrate paleontology were the contributions of USGS geologists exceeded by scientists at other institutions.

The USGS was one of the premiere scientific institutions in the country at the turn of the 20th century, and it sent geologists of outstanding skills to New Mexico Territory to conduct research programs focused primarily on mineral and coal deposits, stratigraphy, and water resources. Mapping and regional geologic studies were essential to these studies, and much new information, both of a general nature as well as on areas of geology such as volcanic features, was assembled as the main research projects advanced. Most of these survey geologists were highly competent, and several, such as Darton, Lindgren, Meinzer, and Lee, were among the most accomplished (one might even say brilliant) geologists working in the U.S. at the time. In reading the dozens of USGS publications on New Mexico geology in the 1900–1915 period, one is impressed with the level of detail and high quality of the work, especially given the reconnaissance nature of many of these studies, and the breadth of geographic coverage within the territory as well. The difficult terrain in many areas, in which roads were poor to nonexistent, and the primitive means of transportation available made field work slow and laborious, and only a few months during the summer were available for such work. The amount of information these men coaxed from the rocks under these conditions is little short of amazing.

In many areas of New Mexico geology, studies just before and around the time of statehood established the foundations of knowledge in these areas, and often the beginnings of regional syntheses of geologic history. In some cases, these studies were the authoritative sources of information for decades. In others, especially including coal studies, stratigraphy and paleontology, water resources, and regional studies accompanied by geologic mapping, the efforts of survey geologists continued unabated for many decades after 1912. Darton's (1928) remarkable book on the geology of the state incorporates much work and new information assembled by survey geologists after 1912 and provides an excellent insight into knowledge of New Mexico geology about 15 years after statehood was attained. As time passed, the survey's work was gradually and increasingly augmented by contributions from in-state institutions, especially the New Mexico Bureau of Mines and Mineral Resources (established in 1927), and a revived geology department at the University of New Mexico (in the 1930s and 1940s).

Our knowledge of all aspects of the geology of New Mexico has obviously increased enormously in the past century. Research by several generations of earth scientists on every facet of the state's geologic record has produced a far more detailed and robust understanding of this record than was available in 1912. We now know that some of what was believed at that time to be true about the state's geologic history, and the processes that shaped it, was woefully incomplete or even erroneous. That does not diminish the accomplishments of the geologists who were building knowledge of the state's geologic record a century ago. They observed and recorded much information and were correct in many of their interpretations, providing strong foundations for subsequent studies.

New techniques and intellectual models have been developed since 1912 that have strongly influenced our ability to accurately understand the state's rock record. It is worth noting that two of the most important of these—the exact dating of rocks by radiometric means, and the regional interpretation of geologic events and history in terms of plate tectonics—were just beginning to be developed when New Mexico became a state. In both cases, it would be more than a half century before either began to be applied to the study of New Mexico geology. The roots of paradigm-changing ideas, which we take for granted in the way we think about and conduct research in geology today, often extend more deeply into the past than most of us realize.

Few of the papers of the late territorial period mentioned here are read or cited by modern geologists, and the substantial contributions to knowledge of New Mexico geology made by early 20th century geologists go largely unrecognized. This is unfortunate, for these geologists include some of the most perceptive and productive men ever to have studied the geology of the state, and in one way or another many current lines of research can be traced back to their studies.

Each new generation of geoscientists to work in New Mexico advances existing knowledge, normally in small incremental steps, but these occasionally lead to major conceptual advances. The recognition of giant calderas as the sources for thick sequences of early Cenozoic volcanic rocks in southwestern New Mexico, and the delineation of major crustal movements and interactions more than a billion years ago from study of Precambrian rocks are two examples. The magnificent edifice of knowledge of the geologic history of New Mexico and all of its varied manifestations increases each year. Yet as time passes we become further removed from the foundations of this edifice as the details of current research cover and obscure them, and likewise removed from those who, a century and more ago, constructed the foundations. One of the main purposes of histories like this is to remind us that what we know now is the result of a long process of investigation, along multiple paths, replete with frustrating pauses, frequent disagreements about evidence or interpretations, and sometimes ventures into blind alleys, which began with early geologists attempting to make sense of what they observed in the varied New Mexico geologic terranes that are often of great temporal and structural complexity.

These early geologists were working in a world that not only was sociologically and technologically much different from our 21st century world, but also within an intellectual framework within the geosciences that, especially in the dominant paradigms of the time, was in some cases significantly different than that which prevails today. Yet the methods of observation and interpretation employed by geologists of a century or more ago in New Mexico—involving above all the rigorous application of the scientific method—are the same as today. Isaac Newton's famous comment about seeing further into the nature of things because he was standing on the shoulders of giants applies equally well to those who study the geology of New Mexico today.

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