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Celebrating New Mexico's Centennial

**References from Parts 1, 2, 3, and 4 have been combined and moved to one master list after Part 4. Also, all duplicated references have been removed.*

Celebrating New Mexico's Centennial

The geology of New Mexico as understood in 1912: an essay for the centennial of New Mexico statehood Part 1

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Introduction

New Mexico became the 47th state of the United States on January 6, 1912, some 66 years after American administration was established at the beginning of the Mexican War in 1846. Observations of the geology of New Mexico began to be made as soon as American soldiers entered the territory, mainly by members of the Army Corps of Topographical Engineers traveling with the invading army. Immediately after the war much additional information was recorded by military men (e.g., Simpson 1850) and by geologists attached to exploring expeditions organized by the federal government, two of them to ascertain potential routes for a transcontinental railroad (the Pacific Railroad expeditions led by Whipple in 1853 and by Pope and Parke in 1854–1855). Reports by geologists and paleontologists such as Antisell (1856), Blake (1856), Hall (1856), Marcou (1858), Shumard (1858, 1859), and Newberry (1861) covered large areas of New Mexico in a reconnaissance manner and laid the foundations for initial general understanding of the geology of many parts of the territory (see Kues 1985a, b, 1992, 2006, 2008a, and references therein for detailed accounts of these early studies).

Geologic exploration of New Mexico continued after the Civil War (1861–1865). Of the four great scientific surveys of the West (King, Hayden, Wheeler, Powell) sponsored by the federal government in the 1860s and 1870s, the Wheeler Survey was by far the most important in adding to knowledge of New Mexico geology. Geologists of extraordinary skills, such as G. K. Gilbert, J. J. Stevenson, and the paleontologist E. D. Cope, spent months in various parts of New Mexico while attached to the Wheeler Survey and wrote long scholarly accounts of their observations and interpretations of the territory's geology and paleontology. To these efforts should be added the long-delayed publication (1876) of J. S. Newberry's geologic observations while a member of the Macomb Expedition in 1859 and 1860. These separate surveys were abolished in the late 1870s, and all federal geologic work was united in the new U.S. Geological Survey (USGS) in 1879. Geologists of the USGS would be the primary force in furthering knowledge of New Mexico geology in the late 19th and early 20th centuries.

Three major trends in the development of New Mexico during the last half of the 19th century emphasized the importance of knowledge of the territory's geology. First, beginning in the 1850s but expanding greatly after the Civil War, was the search for economically valuable geologic resources, initially precious metals and later coal (Christiansen 1974). Dozens of important gold and silver strikes brought thousands of miners into the territory, led to the establishment of hundreds of towns (few of which survived more than a few years), and were a major factor in the economy of New Mexico until 1893.

Second, the entry of railroads, beginning late in 1878 with the laying of track across Raton Pass, revolutionized transportation in the territory, provided the means for moving ore from mines to smelters more quickly and cheaply, and themselves generated a great demand for coal from local deposits to fuel steam locomotives. In just three years (by 1881) more than 1,000 miles of railroad track had been constructed across New Mexico (Myrick 1970), from its northern to southern borders. After a lull in the 1890s, an additional 1,200 miles of track were laid from 1901 to 1910, bringing the total in the territory to about 3,000 miles by the time of statehood.

Third, a five-fold increase in New Mexico's population from 1850 to 1910 documents a great influx of people into the territory. Many sought land for farming and ranching. The Homestead Act of 1862 in particular spurred immigration by making it possible for settlers in New Mexico to acquire as much as 1,120 acres (nearly 2 square miles) of land per family (Williams 1986a). During the 1880s and 1890s the expanding railroads opened access to vast areas for homesteader settlement; towns sprang up and grew, and agriculture and commerce expanded. Accompanying this growth in population was a persistent need for information about the natural environment, climate, the nature and quality of soils, and especially the availability of water. The expansion of mining, railroads, and population in the late 19th century all made geologic studies of New Mexico Territory essential.

The aim of this contribution is to survey the state of knowledge of New Mexico geology in 1912, as the territory became a state. An appreciation of the understanding of the geology of New Mexico 100 years ago is useful for several reasons. It provides a vantage point from which to view the impressive accumulation of geologic knowledge since American administration began in 1846, when virtually nothing was known of the geology of New Mexico. In addition, geologic studies in the territory up to 1912 reflect the ideas, paradigms, and methods of investigation and interpretation that were current in the geosciences then, and thus provide perspectives on the advances our discipline has experienced since then. Third, geologic studies up to 1912 were beginning to be applied to large-scale projects, particularly in irrigation, that would benefit the citizens of New Mexico, some of which have endured to the present. And finally, by appreciating what was known about New Mexico geology in 1912, contemporary geoscientists can better understand the great increases in our knowledge that several generations of their predecessors produced over the past century.

Before beginning our survey of New Mexico geology as understood in 1912 we will first examine some general features of the territory as it transitioned into statehood.

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.

A Snapshot of New Mexico in 1912

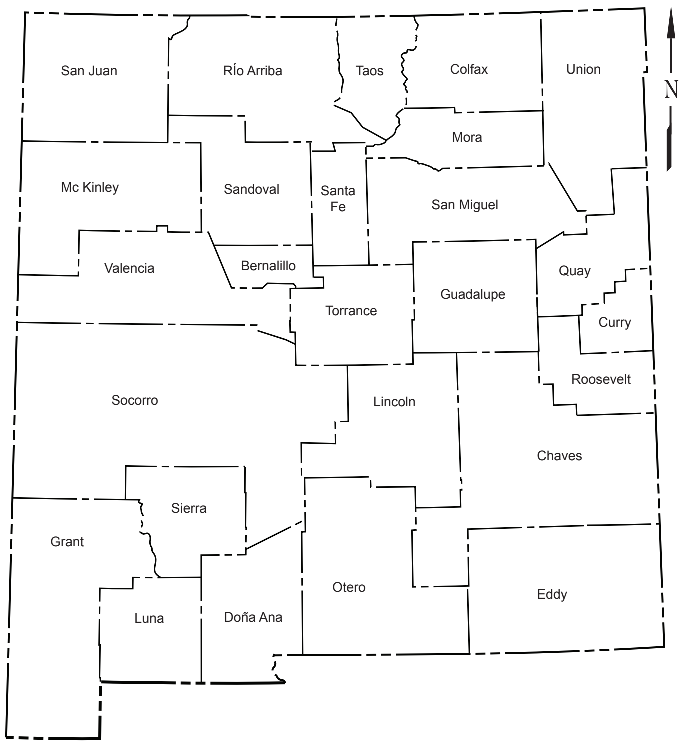

FIGURE 1—New Mexico counties in 1912 (after Beck and Haase 1969).

TABLE 1—Population of New Mexico's 10 largest towns (1910 census). Albuquerque figure includes Albuquerque town (11,020) plus population of contiguous Old Albuquerque precinct. Las Vegas includes the combined population of the separate but contiguous towns of East and West Las Vegas. For comparison the present (2010 census) populations of these towns are shown, and their percent increase over the past century.

	1910	2010	Increase (%)
Albuquerque	13,163	545,862	4,046
Las Vegas	6,934	13,753	98
Roswell	6,172	48,366	684
Santa Fe	5,072	67,947	1,240
Raton	4,539	6,885	52
Las Cruces	3,836	97,618	2,445
Clovis	3,255	37,775	1,061
Silver City	3,217	10,315	221
Tucumcari	2,525	5,363	112
Gallup	2,204	21,678	884

Geography and population

The state of New Mexico, as constituted in 1912, occupied the same area, 121,598 square miles, as it does today, but consisted of 26 instead of the present 33 counties (Fig. 1). De Baca and Lea (1917), Hidalgo (1919), Catron and Harding (1921), Los Alamos (1949), and Cibola (1982) Counties all were created after statehood was attained. About 335,000 people (extrapolated from the 1910 census population of 327,301) lived in the new state in 1912 (0.35% of the approximately 94 million residents of the U.S.), compared to the present population (2010 census) of 2.059 million (0.65% of U.S. population). The population density was 2.75 people per square mile (only Arizona, Nevada, and Wyoming were less densely populated), and the large majority of New Mexico's population lived on farms and ranches and in small communities. Only 14% of New Mexico's population was classified as urban (living in towns and cities with 2,500 or more people) by the Census Bureau; only North and South Dakota, Arkansas, and Mississippi had a lower percentage of urban dwellers, and the U.S. average was 46%. Today, New Mexico's population is about 75% urban.

Then, as now, Albuquerque was the largest city in the state, but it had a population of only 11,000 people (13,000 if the adjacent precinct of Old Albuquerque is included; Table 1), compared to its current population (546,000 in 2010). Viewed another way, the population of Albuquerque in 1910 represented only 4% of New Mexico's total population, whereas the population of Albuquerque in 2010 represented 27% of the state's total population (or more than 35% if the entire Albuquerque urbanized area is considered). In 1912, then, New Mexico was a rural state with few cities and towns, and even the largest of these was hardly a dominant urban center.

Economy

The economy of New Mexico in 1912 was miniscule by present standards, even adjusted on a per capita basis, and for the decrease in the value of a dollar over the past century. Agriculture, manufacturing, and mining were the main pillars of the small economy; tourism and employment by governmental entities were much less significant than they are today. Agriculture, rapidly increasing as a result of major irrigation projects and the cultivation of new dryland crops, produced products valued at more than $8 million (much of the data in this section are from the Statistical Abstracts of the U.S. and the World Almanac for years around 1912, and Coan 1925). Hay, corn, wheat, and oats were the major plant products, with smaller amounts of barley, cotton, sorghum, sugar beets, and various fruits. Livestock included 1.1 million cattle, 3.8 million sheep (the annual wool clip was valued at $2.8 million), 133,000 horses, as well as smaller numbers of swine, milk cows, and chickens. The number of sheep ranked third in the U.S., after Montana and Wyoming. The number of cattle in New Mexico has increased slightly in the past century, but the number of sheep has declined precipitously to less than a half million (ranked 6th today). About 15% of New Mexico's total area (11.3 million acres) was devoted to farming in 1912, compared with 43 million acres of farms and ranches today, which yield a total annual value of about $2.5 billion for all agricultural products.

In 1912 about 14% (10.9 million acres) of New Mexico's area had recently (by 1909) been set aside in national forests. The state had begun to receive some of the income generated by the national forests (primarily lumbering) from the federal government; the total for 1906–1911 was $134,000. Of much greater economic importance, however, was the transfer of 13.4 million acres of federal land to the new state, to be held in trust for education and other public institutions. Revenue from this land, mainly from geologic resources, is managed by the State Land Office and has added billions of dollars to the New Mexico economy during the past century.

A modest beginning to a tourism industry, in the form of several new national monuments created by the federal government, was in place by 1912. El Morro (1906), Chaco Canyon (1907), Gila Cliff Dwellings (1907), and Gran Quivira (1909) had all been established by the time of statehood. These were managed individually by the Department of Interior, as the National Park Service did not yet exist (it was formed in 1916). The first state parks were not created until the 1930s. Of greater economic importance was the influx of people seeking a cure for tuberculosis in the high, dry climate of New Mexico. Several thousand had moved to the new state by 1912, and many remained after their health improved.

TABLE 2—Value of geologic resources produced in New Mexico in 1911 and 1912 (U.S. Bureau of Mines Yearbooks).

	1911	1912
copper	$507,000	$5,615,000
coal	4,526,000	5,037,000
silver	718,000	945,000
zinc	564,000	936,000
gold	763,000	786,000
stone (granite, sandstone, limestone, marble)	406,000	336,000
lead	133,000	247,000
clays	187,000	190,000
iron	146,000	145,000
sand, gravel	19,000	30,000
lime	13,000	9,000
fluorspar	23,000	1,000
gemstone	27,000	1,000
mineral waters	42,000	small
Total	**$8,176,000**	**$14,931,000**

Manufacturing also contributed significantly to the state's economy, although it represented far less than 1% of the total U.S. manufacturing effort in 1912. The total annual value of manufactured products was about $8 million, of which nearly half was devoted to the construction and repair of railroad facilities and equipment. Next in importance were lumbering and flour and grist milling, with a smaller contribution from wool mills and cement plants. By 1908 the Albuquerque Lumber Co. was the largest manufacturing firm in the Southwest, processing massive amounts of lumber from the Zuni Mountains, and its payroll for more than 1,000 employees exceeded even that of the Santa Fe Railroad (Simmons 1982, p. 332). Some 9,200 barrels of "fermented liquors" were also produced in the state in 1912. In all, about 310 manufacturing establishments provided employment for some 4,800 New Mexicans.

The most important economic activity in New Mexico in 1912 was mining, which produced a total of about $14 million from a variety of resources (Table 2). Copper and coal were by far the most important minerals produced. Copper production increased rapidly from 1911 to 1912 and surpassed the value of coal produced for the first time, owing to the beginning of large-scale open-pit mining at Santa Rita in 1910 and the milling of low-grade ore at Hurley the following year. Production of many of New Mexico's most valuable geologic resources, such as potash, uranium, molybdenum, and especially oil and natural gas, lay in the future. New Mexico's $14 million in mineral production in 1912, even when converted into 2010 dollars (multiply by 22), was small compared to the total annual value of around $10 billion today. In terms of total value of geologic resources produced, New Mexico ranked 34th among the states and territories in 1911 and 29th in 1912. Today, New Mexico's rank is typically among the top seven each year.

Travel

In 1912 New Mexico had nearly 17,000 miles of public roads, which was relatively small for the area of the state (0.14 mile per square mile of area). Only the areas of Arizona, Utah, Wyoming, and Nevada were less accessible to roads. New Mexico's improved roads in 1912 were primarily gravel or a sand-clay mixture, but only the major thoroughfares were graded, drained with culverts, and utilized bridges where necessary. The first New Mexico State Legislature established a highway commission with funds allocated for state roads; counties and towns also subsidized local road construction and maintenance. Road building was accomplished mainly by convict labor. According to Twitchell (1917, p. 249), the best of New Mexico's roads had "mile after mile…where forty miles an hour in a touring car is comfortable riding—if one cares to ride too fast to get the beauties of the scenery." Even in 1912 the speed of autos was of great interest and increasing rapidly; the winner of the 1912 Indianapolis 500 race averaged an amazing (for the time) 79 mph.

The growth of automobile traffic undoubtedly influenced the road building plans of the new state. Auto production had been increasing rapidly (to more than 200,000 cars per year in the U.S. in 1912). Most of these were Model T Fords, produced in Henry Ford's efficient assembly lines; by 1914 the number of Fords produced exceeded the combined total of all other auto manufacturers, and their low price ($850) put them in reach of many middle-class families. However, few autos were present in New Mexico at statehood; only 904 license plates were issued during 1912 (Johnston 2011). Simmons (1982, p. 336) estimated that there were probably no more than 32 cars in all of Albuquerque in 1910, the year the city police department acquired its first auto. Photos of various city and town main streets around 1912 typically show more horse-drawn buggies, carriages, and delivery vans than autos, but business directories of this period do list firms involved in the sale and repair of autos, together with larger numbers of blacksmiths and livery feed and sale stables. Some livery establishments hedged their bets by taking care of autos as well as horses. Auto traffic in 1912 was mainly limited to the cities and towns, some of which had paved roads. Horse-drawn carriages were far more important in town-to-town travel and in rural areas, and most towns were served by stage lines.

The first tentative steps toward a "coast-to-coast highway" (actually a series of connected roads of variable quality) was made in 1910, when the National Highways Association laid out an auto route across the nation. A. L. Westgard was employed to scout a route, and part of it went through New Mexico, along the old Santa Fe Trail to Santa Fe, then south to Los Lunas, and west to Grants, Zuni, and Springerville, Arizona. Westgard made a second trip in 1911, using a somewhat different route (south from Santa Fe along the Rio Grande to Socorro and then west to Magdalena, Datil, Quemado, and Springerville). His auto carried rolls of canvas and wooden planks to allow passage across difficult terrain (see Smith et al. 1983, pp. 3–4, for more details of this "coast-to-coast highway"). Few motorists attempted to drive across the country until the late 1920s, when the national highway system was established and more of the roads were paved. Paving most New Mexico highways took decades. According to the official state highway map of 1930, only a few significant stretches of highways were paved: Roswell to Carlsbad; El Paso to Las Cruces and Lordsburg; Santa Fe to Las Vegas; and Algodones to Albuquerque, Los Lunas, and the Rio Puerco.

"Service stations" for autos did not exist in 1912, although rudimentary gas pumps (invented in 1905) were beginning to appear for curbside fueling and clustered in city lots as "filling stations" in the larger eastern, midwestern, and Pacific Coast towns by then (Vieyra 1979). Few if any such facilities were available for motorists in New Mexico, however. The proliferation of dozens of different gasoline brands and stations providing more service than just fuel did not develop until the late 'teens and 'twenties. Bicycles, however, were common in the streets of cities and towns, and the larger New Mexico cities had trolley systems for mass transit. In Albuquerque, horse-drawn trolleys transitioned to electric street cars in 1904 (Johnson and Dauner 1981).

At statehood, railroads were the primary form of medium- and long-distance transportation in New Mexico. In 1912 about 3,000 miles of track stretched across the state, which amounted to 2.49 miles per 100 square miles of area (compared with the U.S. average of 8.30). However, if measured against population, New Mexico's tracks amounted to 86 miles per 10,000 people, far higher than the U.S. average of 26. Nearly every town of a few hundred inhabitants was situated on a rail line, and many spur lines connected to mining and lumbering camps (Myrick 1970). Since about 1914 New Mexico railroad track mileage has declined, to less than 2,000 miles today. However, the mileage of high-quality paved public roads has multiplied many times with the rise of automobile and truck traffic, and this, together with air traffic, has largely replaced railways in passengers and freight transported.

Airplanes, first flown by the Wright brothers in 1903, were still curiosities in 1912, capable of inspiring excitement and even awe in people in remote places like New Mexico. The first airplane to take flight from New Mexico ascended from the grounds of the territorial fair in Albuquerque in October 1911. The first aerial photos from an airplane followed 2 years later, again over Albuquerque (Johnson and Dauner 1981). Probably no one watching these early flights could foresee the tremendous development of air travel and transport that would follow in the 1920s and 1930s.

Communication

Instantaneous (albeit indirect) person-to-person communication, accomplished by telegraphy since before the Civil War, had arrived in New Mexico in the 1860s, as lines were extended from Denver and Kansas City. Telegraph communication expanded rapidly through the territory, and by making available large amounts of information the telegraph helped to stimulate the growth of local newspapers. By 1912, 126 daily to weekly papers were being published in the new state, compared to less than one-half that total today. By 1912, then, New Mexicans were well integrated into the nation's communications grid and learned quickly of important events happening throughout the country and around the world.

Telegraph and newspaper communication was being augmented rapidly by use of telephones in 1912 New Mexico. In that year there were about 7.7 million telephones in the U.S., mostly in the East, about one telephone for every 12 persons. In 1912 New Mexico 10,349 telephones were in use, about one for every 32 residents (McAllister and Putman 1986). This was four times the number in 1902. By 1912 some of the larger towns had their own telephone companies, but most of the phones were concentrated in hotels, business establishments, and government offices and required the assistance of an operator to make the connection with the intended recipient of a call. Few homes in the new state possessed a telephone, and even by the early 1940s there was only one telephone for every 10 New Mexico residents.

"Wireless telephones," later to be called radio (the term was coined in 1910), were in their infancy. Radio communication was mainly used for ship-to-ship and ship-to-shore messages, although amateur ham radio operators communicated with each other using primitive crystal sets. Commercial radio stations, broadcasting scheduled programs to a wide audience, would not arrive until the early 1920s. New Mexico's first radio station, KOB in Albuquerque, was established in 1922 (Williams 1986b).

The bulk of person-to-person communication in 1912 was done by hand-written letters and postcards delivered by the U.S. mail, a practice that is fast fading today with the explosion of electronic communication. There were far more post offices in New Mexico 100 years ago than there are today; virtually every town that existed for more than one or two years and had a few dozen residents boasted a post office (see Julyan 1996). Mail was carried long distances by railroads to major towns and then distributed by hundreds of local delivery routes to small town post offices, and into rural areas, no matter how remote. Rural free delivery service, initiated in 1902, brought mail to those who lived far from post offices, and the mail was delivered by horse and buggy until 1914, when the service motorized. A postcard cost one cent to send, whereas letters required a two-cent stamp (about the same in terms of actual value as today's 45-cent cost to mail a letter). The postal service not only allowed reasonably rapid communication (generally one to a few days depending on distance) between individuals anywhere in the country, but it also delivered mail-order catalogs and the purchases made from them to people in rural communities, allowing them to order items that might not otherwise be available to them within 100 miles or more distance to the nearest large town.

Politics

Before becoming a state New Mexico had elected a senate of 24 members (17 Republicans or Progressive Republicans) and a house of 49 members (33 Republicans/Progressive Republicans), but a governor, William C. McDonald, who was a Democrat. One of the first items of business for the new state legislature was to select New Mexico's first U.S. senators (direct election of senators by the people—Amendment 17—was not ratified until 1913). Thomas B. Catron (5 year term) and Albert B. Fall (1 year term), both Republicans, were selected. Fall was re-elected in 1913 and 1919 but resigned from the Senate in 1921 to become secretary of the Department of the Interior in the Harding administration. He was subsequently (1929) convicted of taking $200,000 in bribes in the Teapot Dome scandal. In essence, while secretary, he leased petroleum from public lands in Wyoming and California that was allocated by the U.S. Navy to two oil men, Sinclair and Doheny, without competitive bidding, and he received large kickbacks in return. Fall was disgraced, paid a large fine, and spent a year in prison—an unfortunate end to the career of a man who had been the first of only four New Mexicans in the cabinet of a president (the others being Clinton Anderson, Agriculture Department, 1945–1948; Manuel Lujan, Interior Department, 1989–1993; and Bill Richardson, Energy Department, 1998–2001). Harvey Fergusson, a Democrat, and George Curry, a Republican, were elected New Mexico's first congressmen.

Women did not vote in these elections, nor did they serve in the first state legislature. In 1912 women could vote in state elections in only 10 states (none of which was New Mexico), and universal voting rights for women only came with the passage of the Nineteenth Amendment in 1920. Native Americans could not vote at all anywhere in the U.S. in 1912, as they did not become American citizens until 1924.

Late in 1912 New Mexicans participated in their first presidential election, one of the most complex in American history (Chace 2004). Four major candidates ran for president: William H. Taft (the Republican incumbent), Woodrow Wilson (Democrat), Teddy Roosevelt (Progressive, and former president), and Eugene Debs (Socialist). New Mexico voted for the winner, Wilson, who received 43% of the vote. This was somewhat of a surprise, as Republicans dominated the state legislature, and Taft had been an enthusiastic supporter of statehood and had signed the legislation that had made New Mexico a state.

Education

Education in the state in 1912 was rudimentary by present standards but was probably not unusual for the time. Of an estimated school-age (5 to 21 years) population of 100,000, only about 40,000 regularly attended public and private schools. There they were taught by a statewide total of about 1,600 teachers, most of them women, who earned an average annual salary of $390 (Twitchell 1917, p. 130). Teacher training was limited; most public school teachers lacked even a high school education, and Twitchell (1917, p. 174) thought it praiseworthy that most New Mexico schools employed at least one teacher who had two to four years of high school education. The average length of the school term was 125 days, and state regulations mandated that schools must be open for at least five months of the year. One of the acts of the first New Mexico state legislature was to establish at least one high school in each county; 14 high schools existed by the end of 1912. Given the state of public education in New Mexico it is probably surprising that only 20% of the adult population was illiterate.

During the first few years of statehood, New Mexico's institutions of higher education were in their infancy, and included courses that today would be considered at the level of high schools. About 1,000 students were attending the state's nine institutions of higher education in 1912. These were University of New Mexico (Albuquerque); New Mexico College of Agriculture and Mechanical Arts (Las Cruces, now New Mexico State University); New Mexico School of Mines (Socorro, now New

Mexico Institute of Mining and Technology); New Mexico Normal University (Las Vegas, now New Mexico Highlands University); New Mexico Normal School (Silver City, now Western New Mexico University); Spanish-American Normal School (El Rito, now Northern New Mexico College); New Mexico Military Institute (Roswell); New Mexico Institute for the Blind (Alamogordo); and New Mexico School for the Deaf and Dumb (Santa Fe). Of these institutions the largest was the Las Cruces college, with 42 professors and 370 students (Statesman's Yearbook 1913); UNM employed 22 professors to teach 137 students, and the New Mexico School of Mines eight professors for 34 students. No graduate programs existed at any New Mexico institution. Presently, by contrast, at least 25 institutions of higher education exist in New Mexico, with a total enrollment of about 200,000 (Vigil-Giron 2005).

In 1912 some $954,000 was expended for public schools and $381,000 for higher education (Twitchell 1917, p. 130). Education expenditures were the single largest item of the state budget and represented more than a third of the state's total expenditures of about $3 million. Today, education remains the single largest area of expenditures for New Mexico, but has risen to more than one-half of the total budget of about $5.5 billion.

Daily life

The first decade of the 20th century witnessed many innovations that were becoming, or would grow to become, basic elements of modern American society; the advent of autos, airplanes, telephones, and early forms of radio was noted above. People living in New Mexico, and indeed throughout the U.S. in 1912, experienced more rapid scientific and technological change, and therefore societal changes, than had any previous generation. The pace of change would only increase through the 20th century, driven in part by bursts in technological advances accompanying two horrendous world wars and dozens of smaller conflicts. Looking back 100 years, to the fabric of the lives and culture of New Mexicans in 1912, we see much that is recognizable (the more so the older we are and the farther back our memories extend), but much that seems completely archaic in the context of our own late 20th and early 21st century experiences. Here, I sketch a few selected aspects of the daily lives of New Mexicans as statehood was attained.

First, people lived considerably shorter lives. The average life span at birth in the U.S. in 1912 was 51.5 years for men and 55.9 years for women (average = 53.5 years), compared with 75.7 years (men), 80.7 years (women) and 78.1 years (average) in 2009 (U.S. Census Bureau). Tuberculosis and pneumonia were the leading causes of death 100 years ago; now it is heart disease and cancer. Medical knowledge and practice, and access to it by the public, have increased tremendously. In 1912, although the bacterial causes of some diseases were known, and anesthesia was used in surgery, knowledge of viruses and antibiotics, the use of X-rays, and myriads of advances in understanding and treating the biologic, genetic, and environmental causes of diseases, as well as in surgical practices, organ replacement, and so on lay in the future. The realization that inadequate diet could cause debilitating diseases, such as scurvy, beriberi, pellagra, and rickets, was just beginning to be understood in 1912. Certain organic molecules (amines) were first identified as necessary dietary constituents in 1912 by the Polish biochemist Casimir Funk, who coined the term vitamin for the first one he discovered (B1, or thiamine) (Bryson 2011, pp. 197–198). As New Mexico became a state, however, the relationship between vitamins and diseases had not become widely accepted. More than 90% of babies were born at home, and most people died in their homes. Small hospitals were present only in the larger New Mexico towns, and these were operated mainly by churches.

In addition, because the causes and treatments of many diseases were unknown, people turned to hundreds of widely advertised "patent medicines," which claimed to cure any disease or ailment, but which contained a large variety of ineffective or dangerous ingredients, generally mixed in alcohol. The health hazards of these "medicines," as well as the widespread adulteration of food products, was just beginning to be recognized (e.g., Sinclair 1906) and curtailed in the early 20th century. For example, laudanum (a highly addictive mixture of 10% powdered opium in alcohol) and similar elixirs were widely used to reduce pain, induce sleep, and relieve everything from colds to cardiac diseases and menstrual cramps (Wikipedia, "Laudanum"; "Patent Medicines"). Passage of the Pure Food and Drug Act of 1906 helped, but it required only that the ingredients of any product be listed on the label; laudanum and many other harmful "medicines" continued to be sold over the counter. Strong regulation and testing of food and drugs came only in 1938, with passage of the Food, Drug, and Cosmetics Act. One medicine of indisputable value, however, was available to late-territorial New Mexicans; aspirin was first marketed in 1899.

Life in 1912 was considerably more labor intensive than it is today. The use of electricity in lighting and power generation was well established and expanding rapidly; most towns had light and power companies, and electric street lights as well as lighting in hotels, businesses, and in some residences were becoming common. However, smaller towns and rural areas often lacked electricity; this changed only with the great expansion of rural electrification programs in the 1930s. Even so, consumer products run by electricity were becoming available to the middle class. From 1891 to 1910 electric fans, vacuum cleaners, washing machines, irons, and toasters began to appear in the homes of those who could afford them (Bryson 2011, p. 158). Other equally useful but more inconspicuous implements invented in the late 19th century (e.g., mousetraps, paper clips, the zipper, safety pins) were also becoming available to late-territorial New Mexicans.

Indoor plumbing was a luxury, even in towns. The better hotels proudly proclaimed the availability of "hot and cold running water" (together with telephones and electric lights). However, even as late as 1940, 41% of dwellings in New Mexico lacked running water (Vigil-Giron 2005). Sewer systems were being constructed in the larger towns, but generally sewage was little treated. Albuquerque's sewer system, for example, simply routed the wastes into the Rio Grande (Johnson and Dauner 1981).

Such labor-saving devices as refrigerators were available on an industrial scale, but were not yet in homes. Most towns had ice plants, the largest of which (in Albuquerque) could produce as much as 45 tons per day (Simmons 1982). Ice was delivered to homes regularly from the plants, at a cost of 50–75 cents per pound. Food spoilage and its health risks were a constant problem. Most homes were heated either by wood or coal; mines near Gallup and Madrid provided most of the coal needed in Albuquerque.

The standard of living for most New Mexicans was considerably lower in 1912 than today. According to one study (Klein 2009), the per capita income for the U.S. in 1910 was only about $300. A wage earner in manufacturing or other industry averaged about $720 per year in income, with some specialized positions paying considerably more than $1,000 per year (for these and following monetary figures, remember that one dollar in 1912 had the purchasing power of about $22 in 2010). The average wage earner was paid about 20–25 cents per hour, and worked 50 or more hours per week (Fisk 2003).

The per-capita income of New Mexico in 1910 was $201 (Klein 2009), considerably less than the national average and ranking 38th of the (then) 48 states and territories. This amounts to about $4,400 in 2010 dollars, compared with a 2009 per-capita income of $32,992 (U.S. Census Bureau). New Mexico's current low ranking among the states (42nd of 50) has changed little in the past century. It is also important to keep in mind that New Mexico wage earners in 1912 included children (no child labor laws, although the problem was much worse in the industrial cities of the East and Midwest), and no social safety nets, such as unemployment benefits, social security, pensions, or health care plans existed at the time. The life of an average New Mexican working man at statehood was considerably more precarious than it is today.

Income earned by New Mexicans in 1912 was used, as today, for the necessities of life, and for some people (a much smaller proportion than today) luxuries were also possible. Prices of common items (1911 wholesale prices, from World Almanac 1912) provide an insight into the expenses of living a century ago (again, multiply by 22 to obtain comparable 2010 prices): loaf of bread, 4 cents; eggs, 35 cents per dozen; bacon, 9 cents per pound; milk, 5 cents per quart; coffee, 15 cents per pound; beef, 12 cents per pound; print cloth, 3 cents per yard. A barrel of crude oil cost $1.30, and bituminous coal went for $3.15 per ton. A good horse might cost $195. January 1912 issues of the *Albuquerque Morning Journal* advertised men's overcoats for $15–$20; hats for $1.95; dress shirt, 90 cents; women's cloth skirts, $3. A four-room house and lot in town cost $1,900–$2,300, but one would have had to pay $4,500 for a more luxurious seven-room house. When traveling, a room in a good hotel would cost $1–$2.50 a night; and 25 cents to $1 would buy a large dinner.

Payment for many purchases was made with silver (10, 25, 50 cent, and dollar) and gold (2 ½, 5, 10, 20 dollar) coins, although copper and copper-nickel coins (1, 5 cent) and bills also circulated widely. The price of silver in January 1912 was 55 cents per ounce, less than half of its inflation-adjusted value today (ca. $30 per ounce), and gold was $20.67 per ounce, about one-third of its present inflation-adjusted value of around $1,600 per ounce. If one had the means in 1912 he could take 30 to 40 $20 gold coins and purchase a deluxe Ford Model T touring car. Today, 20 to 30 $20 gold coins (when converted into modern paper currency) will buy an equally luxurious auto. The purchasing power of gold and silver, unlike that of the dollar, has actually increased through the past century.

When the work was done, a middle-class New Mexican in 1912 had many entertainment options—orchestral concerts in a park, silent movies (tickets cost 5 or 10 cents) or vaudeville shows (in the larger towns), amusement parks, a traveling circus, picnics. If in Santa Fe, a visit to the newly founded Museum of New Mexico, in the Palace of the Governors, was a possibility, and county fairs during the summer attracted many people. Baseball was without doubt "the national pastime"; many towns formed local teams, and professional baseball leagues covered much of the country. Professional football and basketball did not exist (college teams, especially in the East and Midwest, attracted many fans), and hockey was limited to Canada, but boxing, wrestling, and tennis were popular sports.

Photography was an increasingly popular pastime. Dry-plate cameras, in which a glass plate coated with gelatinized light-sensitive chemicals was exposed, and the plate then developed in a bath of chemicals, was still the choice of professional photographers in the early 1900s. However, their use involved unwieldy equipment and time spent with messy chemicals in order to develop an image. George Eastman had invented a camera using a roll of celluloid film in 1889, and in 1900 introduced and mass-marketed an inexpensive box camera called the "Brownie." These could be carried easily, used a six-snapshot film cartridge that could be sent to the Kodak lab for developing and printing, allowed a person to instantly photograph an ephemeral scene, and were so simple to operate (essentially point-and-shoot) that a child could take photographs. The earliest Brownies sold for a dollar, plus 15 cents for a film cartridge. By 1912 one could still buy the cheapest model for a dollar (or spend as much as $12 for a deluxe folding camera with a better lens and shutter), and a developing box was available for those who wished to make their own prints. Millions of Brownies had been sold by 1912, and their use revolutionized the preservation of photographic records of daily life.

At home, the wealthy family might have a phonograph machine to play music recorded on either a cylinder with a grooved surface, initially of hard wax but by 1912 of celluloid plastic, or a gramophone disk (record) composed of shellac (vinyl appeared in the 1920s). Records were finding greater favor with the public in 1912 (because of more recording time and easier storage), and cylinders eventually became extinct in the 1920s, but there was little difference in sound quality (Wikipedia, "Phonograph Cylinders"). More commonly a member of a family, often a daughter, played a musical instrument for the entertainment of family and friends.

Public libraries were considered important, and most of the larger towns in 1912 New Mexico had one, since the first was established in Cimarron in 1881. Many were established through fund-raising efforts by civic-minded women, and in the early years of the 20th century, Albuquerque's public library was considered to be the largest and best in the Southwest (Rex 1986). The building of libraries in towns across the U.S. was considerably enhanced by grants made by Andrew Carnegie, a Scottish-born steel magnate. From 1889 to 1929 Carnegie's foundation subsidized the construction of nearly 1,700 libraries in the U.S. Three were built in New Mexico (in Raton, Las Vegas, and Roswell) from 1902 to 1911 at a total cost of $32,000 (Wikipedia, "Carnegie libraries").

The shelves of many of these libraries (in New Mexico and across the U.S.) undoubtedly held books about New Mexico. Most of the dozens that had been published were the accounts of explorers, military men, and scientists who had visited the territory since the time it had passed to American administration. Many of these also contained art, ranging from simple sketches to fully realized watercolor paintings, which gave readers a visual appreciation of the people, towns, and natural landscapes of the territory. Books of fiction set in the territory, however, were few. The earliest and best known New Mexico novel is *The Delight Makers* (1890) by the anthropologist Adolph Bandelier, but only a few others had been published by 1912 (Cohen 1986). Use of New Mexico as a locale, or in some cases a protagonist, in novels would accelerate in the 1920s, and today of course the state has been portrayed in hundreds of novels.

By the time New Mexico became a state, its unique cultural and environmental qualities, as well as its wonderful natural light, were also coming to be recognized by early film makers. Thomas Edison experimented with the process near Cerrillos before the end of the 19th century, and the first actual (experimental) movie shot in the territory, *Indian Day School*, only a few minutes long, was filmed in 1898 in Isleta Pueblo. By 1912 several silent movies starring such noted actresses as Mary Pickford and Mabel Normand had been filmed in New Mexico (Williams 1986c).

And, beginning in 1898, when two eastern artists (Bert G. Phillips and Ernest Blumenschein) on their way to Mexico stopped in Taos to have a broken wagon wheel fixed, a group of artists gradually began to live or spend summers in Taos. Entranced by the landscape and light and native cultures, they painted local subjects with a palette of vibrant colors, and became internationally known. They called themselves the "Taos artists colony," and in 1915 formalized their association as the Taos Society of Artists. Their work represents the pinnacle of late territorial/early statehood artistic expression in New Mexico.

Geology in New Mexico around 1912

During the decade before statehood, New Mexico geology was being studied to a degree that far exceeded that of any previous decade. Geologists were actively engaged in field studies in many parts of the territory, both in order to fill in the many blank spots in geologic knowledge of areas, and to gain a better understanding of rocks in which important deposits of minerals, and other resources such as coal and water, were found. The large majority of geologists active in New Mexico during this time worked for the USGS.

By its 25th anniversary in 1904, the USGS was the pre-eminent geologic institution in the country. The survey had attracted an outstanding staff of geologists, many of them from academia but some, such as N. H. Darton, who were largely self taught and lacked college degrees, and they in turn trained younger men recently graduated from academic geology programs. The survey's work encompassed a broad spectrum of disciplines and ranged from practical to theoretical. Fundamental research on rock composition and structure, including experimental and theoretical studies, was conducted together with broad programs of field and regional geology involving stratigraphy, paleontology, volcanology, and structural geology. Study of the geology of mining districts and of water resources, both on the surface (involving hundreds of gaging stations along rivers) and within the ground, were within the survey's purview, as was the classification of forested and irrigable lands (Frazier and Heckler 1972; Rabbitt 1989).

During this time the USGS also was producing an ever-increasing number of topographic maps (by 1904 for more than a quarter of the U.S.), and the number of geologic maps for portions of the U.S. was increasing rapidly. Survey research was published almost continuously in a mounting series of bulletins, professional papers, and water-supply papers. An ambitious program to create a geologic atlas of the country, via separately issued folios of large quadrangles or other areas, had begun in the 1890s. Each folio included a topographic and geologic map of an area, and comprised a mini-treatise on its geology. However, although more than 150 folios had been published by 1912, none covered any part of New Mexico, although the field work leading eventually to the first two New Mexico folios (Silver City, Paige 1916; Luna County, Darton 1917b) had begun by 1910.

By 1912, the USGS was in a state of transition. Much work on forested lands was transferred to a newly established Forest Service in 1905; the Reclamation Service, charged with evaluating and improving access to water, became independent in 1907 (Frazier and Heckler 1972); and the Bureau of Mines was detached as a separate agency in 1910. Some noted that more of the survey's activities involved "practical" endeavors, such as topographic mapping and water and mineral resource evaluation, more than geologic research (Rabbitt 1989). In New Mexico in the years just before statehood, USGS geologists were mainly involved in programs studying ore deposits, the occurrence of coal, and water resource evaluation. However, field geologic studies were essential to such projects, and a considerable number of fundamental, outstanding geologic studies were published.

Several main lines of USGS field research in New Mexico had developed by 1905, and these would broaden and diversify as time went on. The first was an effort to better understand the geology of west Texas and especially the putatively Permian sequence in the Guadalupe Mountains and neighboring areas, by G. H. Girty and G. B. Richardson. These studies led inevitably across the border into southern New Mexico as individual units and facies were traced northward. Second, in 1905 the USGS initiated a program of detailed studies of New Mexico's metallic resources and their geologic contexts, which resulted in the publication of one of the classic works of New Mexico geology, *The ore deposits of New Mexico*, by Lindgren et al. (1910) (see below). Third, another major USGS program initiated in 1905 was the study of the territory's coal resources, which necessarily involved much work on Cretaceous stratigraphy. Fourth, in response to the need for better control of Rio Grande and Pecos River flow, for flood control and irrigation, the survey initiated large-scale engineering projects on both rivers, which required a good deal of additional expertise in water resources, agriculture, and local geology.

The survey geologists sent to study these various aspects of New Mexico geology were an extraordinarily talented group, and many of their studies were not limited to a single research area but cross-fertilized each other. Two of the *Ore deposits* authors, Graton and Gordon, also examined sedimentary strata in the areas where they worked, and they began to develop a regional stratigraphic framework for the Paleozoic. Willis Lee, originally assigned to study the water resources along the Rio Grande, soon moved extensively into Paleozoic stratigraphy, and then was the major contributor to studies of New Mexico's Cretaceous stratigraphy as part of the survey's coal studies program. Finally, after these efforts were underway, the mapping, field, and regional geologic studies of N. H. Darton had begun by 1912. Darton's contributions mostly postdated the attainment of statehood, and they would culminate in 1928 with the first great synthesis of New Mexico geology, together with the first modern geologic map of the state.

FIGURE 2—Waldemar Lindgren, USGS (Robertson 1993).

Of many important studies published by survey geologists around the time New Mexico became a state, probably the finest single publication on New Mexico geology to appear in the years leading up to statehood was *The ore deposits of New Mexico*, Professional Paper 68, by Lindgren, Graton, and Gordon (1910). This is far more than a comprehensive description of ore deposits; it includes detailed information on stratigraphy, structure, volcanic and intrusive rocks, and a synthesis of the geologic history of the territory, which makes it the closest approximation to a book on the geology of New Mexico as existed in 1912. This work will be referenced many times in the following narrative. Its authors exemplify the high caliber of geologists employed by the USGS during this time, and the excellent standards of scholarship by the survey in the first decade of the 20th century.

Waldemar Lindgren (1860–1939; Fig. 2) was born in Sweden and came to the U.S. with a degree in mining engineering (1882) from the University of Freiburg, Germany. He was hired by the USGS in 1884 and spent the next 25 years studying and publishing prodigiously on the geology of mining districts in California and other western states, and establishing himself as one of the leading theorists on the origin of ore deposits. He became chief of the metals branch of the survey in 1907 and chief geologist in 1911. The following year he moved to M.I.T. as chairman of its geology department and in 1913 published the first edition of his encyclopedic textbook *Mineral Deposits*. He continued at M.I.T. until his retirement in 1933.

Louis C. Graton (1880–1970) graduated from Cornell University in 1900 and completed doctoral work (except for the dissertation) there in 1903. In that year he joined Lindgren with the USGS in studying the gold-bearing rocks of the Cripple Creek (Colorado) mining district and then moved with Lindgren to study New Mexico's ore deposits. During his six years with the survey Graton became an expert on copper deposits. In 1909 he joined the faculty of Harvard University in mining geology, and he remained at Harvard through a long and distinguished career that involved wide participation as a consultant and member of the boards of directors of many mining companies (Hurlbut 1972).

C. H. Gordon (1857–1934) received his doctorate from the University of Chicago (1895) and then embarked upon a series of teaching positions, spending the 1904–05 academic year as a professor of geology and mineralogy at the New Mexico School of Mines in Socorro, just as the survey was beginning its multifaceted studies of the territory. He joined the USGS in 1905, stayed until 1913, and from 1907 on also served as a professor at the University of Tennessee.

FIGURE 3—Field transportation in the early 1900s, west of the Guadalupe Mountains (Richardson 1904).

FIGURE 4—C. L. Herrick, University of New Mexico (Northrop 1966).

Other geologists who contributed significantly to understanding the geology of New Mexico as the territory transitioned into statehood will be introduced as this narrative proceeds.

A typical USGS geologist would arrive in New Mexico in late spring or early summer by railroad, a journey of four or five days from Washington, D.C., the location of USGS headquarters. According to contemporary accounts (e.g., Morgan and Lucas 2002), meals along the way each cost from $0.60 to $1.25 and a hotel room $2.50 a night. Upon disembarking at a town closest to his field area, the geologist would need to purchase food and water sufficient for several days to a week or two in the field. Transportation, by horse or horse-drawn wagon or buggy (Fig. 3), would be rented or purchased. Wagons could be used for access to areas in which at least rudimentary roads existed, but travel by horse and pack train might be required for excursions to remote or topographically difficult regions. If the field work was lengthy, a local man with a wagon and saddle horse might be hired as cook and camp hand for $150 per month. Motorized vehicles were not used in survey field work until 1917 (Rabbitt 1989). Some geologists, like N. H. Darton, who were working in other areas of the West, would head south to the warmer climates of Arizona or New Mexico for a few weeks of field work in early fall before returning to Washington (King 1949).

Depending on the terrain and location, other measures were necessary. Dave Love (pers. comm., 2010) recounted additional practices from the field notes of Oscar Meinzer, who began water-supply studies of the Tularosa Valley in 1911, resulting in one of the classic works of New Mexico geology (Meinzer and Hare 1915). "Each notebook starts with Meinzer calibrating his buggy-wheel revolution counter with known mileages between Alamogordo and Tularosa. Then he records the number of revolutions at various places during his field work and calculates the number of miles he has gone in that feature-challenged landscape of the central Tularosa Basin. He also sights stars and lights of ranch houses at night to figure out where he is." The prudent geologist would inquire locally concerning roads and springs and other sources of water. He would have brought the relevant topographic maps for his field area, but in New Mexico topographic maps did not exist yet for most of the territory, and so reliance on local maps and information was important.

Although such accounts doubtless exist in unpublished field notes, I have not discovered many published records of field supplies and equipment typically used by a field geologist in New Mexico in the early 1900s. In many respects the methods of making and recording observations in the field have not changed much in the past 100 years. The early 20th century geologist would walk outcrop, observe rock formations and structural features, measure stratigraphic sections, take strike and dip measurements, do plane table/alidade work, and collect rock and fossil samples (which, if voluminous, would be packed up back in town and shipped by rail back East). Binoculars were probably used to trace formation outcrops in distant or inaccessible areas and to observe large-scale structures. Brunton compasses, patented by the Colorado geologist D. W. Brunton in 1894 and soon after manufactured by the William Ainsworth Co. of Denver (Wikipedia, "Brunton compass"), may well have been part of the field geologist's tool kit before 1912.

Photographs of field areas, outcrops, and specific geologic features began to appear in USGS publications in the 1890s and are present in fair abundance in many publications relating to New Mexico geology before statehood. The camera equipment used was probably dry-plate cameras, judging from the quality and dimensions of many of the published photos, a few of which are reproduced in this paper. By 1900 such cameras had become much less bulky and could carry many prepared plates. King (1949, p. 153), in a fine memorial to N. H. Darton, noted that he "made a fine art of his geological photography," and that it "was accomplished with equipment that would seem cumbersome and inferior today—with glass plates and a heavy box camera that had to be carried by hand over mountain peaks and through canyons." It would not be surprising though, if some geologists also carried a roll-film Brownie camera in the field to document important details as a supplement to field notes.

In the years leading up to statehood two New Mexico institutions employed geologists—the University of New Mexico (UNM) and the New Mexico School of Mines (now New Mexico Institute of Mining and Technology). Both had been established in 1889, and both took several years to organize and begin instruction of students, most of whom were college-preparatory (high school) students. At UNM, its second president (1897–1901) was the gifted young geologist Clarence L. Herrick (1858–1904). Herrick (Fig. 4) had been a professor at Denison and Cincinnati universities before arriving in New Mexico in 1894 to take the cure for tuberculosis, contracted the previous year. Trained as a geologist and paleontologist, Herrick was versatile and brilliant, publishing more than 150 papers in such fields as zoology, neurology, and psychobiology in addition to his contributions to the earth sciences (Northrop 1966). After a year as a geologic consultant in Socorro he was named in 1897 as president (and first geology professor) of UNM. Herrick lost no time in constructing a science building at the fledgling university (Hadley Climatological Laboratory, which burned to the ground in 1910) and establishing a bulletin for the publication of scientific research papers (the first in New Mexico), which lasted until the 1960s. He also began a program of geologic field studies that took him to many parts of the territory and resulted in a steady stream of publications describing details of the regional geology (structure, tectonics, igneous geology, geomorphology, in addition to stratigraphy and paleontology) of the large areas he surveyed before his untimely death in 1904. These papers are filled with perceptive observations and ideas, many of which were mentioned only in passing and were later more fully developed by others. Several of them also included the first real geologic maps made of areas of the territory. Herrick mentored one brilliant student (Douglas Johnson, who received the first bachelor's degree in geology awarded in New Mexico); we will encounter both men again later in this paper.

Herrick was succeeded at UNM as geology professor by William G. Tight (1865–1910), who was also the third president (1901–1909) of the university (see Northrop 1966). Tight matriculated at Denison University in Ohio and received his doctorate from the University of Chicago. Tight did little geologic research while at UNM, publishing only one paper involving New Mexico geology. His main contributions to New Mexico geology were twofold. He mentored another outstanding undergraduate student, Kirk Bryan, a native of Albuquerque who would go on to become a professor at Harvard, and return to New Mexico for groundbreaking geomorphic and hydrogeologic studies. And, somehow, Tight persuaded the Geological Society of America to hold its 20th annual winter meeting at UNM in December 1907. A total of 33 geologists, plus several students made the trip to what must have seemed to some (especially the three Canadian attendees) as a small town in the middle of nowhere. Some 42 papers were presented in the Hadley Science Hall at UNM, and Tight led a field trip to the Sandia and Manzanita Mountains, providing an unpublished sketch map of the geology of the area. The USGS was represented by N. H. Darton, who presented three papers, only one of them having to do with New Mexico geology. Charles Rollin Keyes, former president of the New Mexico School of Mines (see below), also presented three papers.

Meanwhile in Socorro, the New Mexico School of Mines had opened in 1893 and awarded its first baccalaureate degrees, in chemistry and mining engineering, in 1896 (much information in the following paragraphs is from Christiansen 1964). By 1912 a few degrees had been awarded also in metallurgical engineering, civil engineering, and general science. Geology courses (but not degrees) also were offered, but the focus of the school was clearly engineering. The school had begun commercial analyses (assaying, water and fuel analysis) in 1907 as a service to the mining industry.

Two early presidents, Fayette Jones (1898–1902) and Charles R. Keyes (1902–1905), were active in matters involving New Mexico geology. Jones (1859–1936) was trained as a mining engineer and pursued a variety of mostly mining-related professions during his life (see Holts 1979, for a short biography). Probably his main contributions in New Mexico occurred after he had left the presidency of the School of Mines and was living in Albuquerque as a consultant and field assistant for the USGS. Governor Otero appointed him to the board preparing the territory's contribution to the 1904 World's Fair in St. Louis. New Mexico's exhibit, organized by the School of Mines with Jones' assistance, focused on mining and geology, and by contemporary accounts was one of the most memorable at the fair. According to Christiansen (1964, p. 17) the exhibit required a full train car to ship. "In the center was a huge relief map of New Mexico twenty feet square. All the mineral products and natural resources in the [territory] were represented in different colors. With this was a large display in color showing the geologic formations in New Mexico. There were several pyramids (eight feet high) of zinc, lead, and copper ores from the Magdalena mining district, as well as four large cases displaying the various minerals found in New Mexico, and a number of pictures of New Mexico emphasizing mines, minerals, and natural resources."

To accompany the exhibit, Jones (1904) wrote a book, *New Mexico Mines and Minerals*, which was an attempt to provide a comprehensive record of New Mexico's mineral resources and the history of their development. It is a fascinating book, with much information derived from correspondence and conversations with mining men throughout the territory, many of whom had lived through the boom times of the 1880s and early 1890s. As Holts (1979, p. 54) noted, the accuracy of some information is questionable in places, and, being published by the New Mexico Bureau of Immigration, it served as promotional tourist and immigrant literature as well as a record of New Mexico's geologic resources.

That Jones included much accurate information in the book is indicated by the fact that Lindgren et al. (1910), in their monograph on New Mexico ore deposits, made much use of it, stating (p. 16) that in Jones' book "for the first time a resume was given of the historical, geologic, and mining features of the various camps of the Territory. This book of reference is quoted frequently in the following pages; it contains a great amount of valuable material, including a list of minerals which forms the base of a similar table in this report. The geologic features are not always adequately treated and are in places erroneously stated, but the work is not claimed to be a geologic treatise."

Jones lived in New Mexico for much of the rest of his life, primarily as a mining consultant but also serving the state in various capacities, including a second term as president of the New Mexico School of Mines (1913–1917). There, in 1915, he established a "New Mexico Mineral Resources Survey" but without any designated state funding, and it published three bulletins between 1915 and 1919. These were ideas ahead of their time; it was not until 1927 that the state established the New Mexico Bureau of Mines and Mineral Resources as a department of the School of Mines, and the bureau began a vigorous publication program, which continues to this day. The School of Mines became the New Mexico Institute of Mining and Technology in 1951.

Charles Rollin Keyes (1864–1942) followed Jones as president of the School of Mines (1902–1905). He received his Ph.D. from Johns Hopkins University in 1892, and by the time of his arrival in Socorro, Keyes had served as chief geologist and paleontologist of the Missouri State Geological Survey, assistant state geologist of Iowa, and director of the Missouri Geological Survey. He had also published extensively on the stratigraphy, paleontology, and economic geology of the Midwest. Keyes' career deserves extended study, for it is unique in the annals of American geology, but only a few comments are made here.

In New Mexico, Keyes began publishing articles on the geology of the territory as soon as he arrived, and Burks and Schilling's (1955) *Bibliography of New Mexico Geology and Mineral Technology through 1950* lists 52 publications from 1903 to 1912, mostly short notes, on a wide variety of subjects, including stratigraphy, coal fields, mineral deposits, structure and tectonics, surface processes, geomorphology, volcanic craters, and ground water. Although he apparently returned to his home state of Iowa a few years after his School of Mines service (even running a losing race for senator from that state in 1918), he continued to publish papers on the geology of New Mexico until the year of his death. His list of publications on the geology of the state is by far the longest of any author cited by Burks and Schilling (1955), yet he had relatively little influence on the development of geologic knowledge of New Mexico. Many of his publications were short, derivative, superficial, and idiosyncratic, and many mainly featured criticism and arguments against mainstream views of the local geology, especially the work of the USGS. He coined dozens of stratigraphic names within a grand but inconsistent concept of New Mexico's geologic history, but these units were little supported by actual field description or establishment of type sections. He preferred the short-lived International Geological Congress convention of ending period names with "-ic" (e.g., Devonic, Cretacic, etc.) to the more familiar USGS forms, and apparently enjoyed publishing his own unorthodox views.

In 1922, Keyes bought the defunct journal *The American Geologist*, renamed it *The Pan-American Geologist*, and thereafter, as publisher and editor, published whatever he wanted, unfettered by peer review, exclusively in that journal. Most of his subsequent articles on New Mexico geology involved little more than opinions, assertions, and criticisms of the well-established views of other geologists, often rehashing arguments that had been settled to everyone else's satisfaction decades ago. Although his early writings on New Mexico stratigraphy and other subjects were referenced and discussed by other workers (e.g., Lindgren et al. 1910), by 1912 much of his work had been dismissed and was ignored as study of New Mexico geology proceeded.

Geologists working in New Mexico (and everywhere else) in the early 20th century were almost exclusively men. The culture of the time discouraged, if not actually prohibited, women from pursuing geology degrees and working as geologists. A few pioneering women obtained graduate degrees in geology in the late 19th century. Mary E. Holmes was the first woman in the U.S. to be awarded a doctoral degree (from the University of Michigan, 1888) and the first to be elected a Fellow of the Geological Society of America. Florence Bascom received her doctorate from Johns Hopkins (1893), was the first woman hired as a geologist by the USGS (1896), and later founded and taught in the geology department of Bryn Mawr College, Pennsylvania. However, these early women geologists were trained in eastern and midwestern universities and worked mainly in those regions. Very few ever found their way to wild and remote New Mexico.

The Burks and Schilling (1955) bibliography of New Mexico geology through 1950 lists only three women who published (a total of five papers) on the geology of New Mexico through 1912. Three of these papers were by Ida H. Ogilvie. She was a student of Bascom's at Bryn Mawr and then received her doctoral degree at Columbia University in 1903 (Wood 1964). She founded and for several decades taught in the geology department at Barnard College in New York City. In 1899, she was part of a field party led by R. D. Salisbury (University of Chicago), which passed through New Mexico on its way to the Grand Canyon. An unusual igneous intrusion through Cretaceous strata near Las Vegas caught her attention, and she published (Ogilvie 1902) a short paper on the composition of these rocks, a camptonite or plagioclase lamprophyre. In the winter of 1904 she studied the geology of the Ortiz Mountains and surrounding area, proposing the term *conoplain* (Ogilvie 1905) for the partly erosional and partly constructional plain that slopes away in all directions from the intrusive core of the mountains—one of the first descriptions of what has come to be called the Ortiz pediment surface. This paper features detailed analyses of erosional processes and stream action in a high-elevation, arid region, and it is one of the earliest important contributions to the study of New Mexico geomorphology. Her third publication (Ogilvie 1908) was a chemical-petrographic analysis of the igneous rocks (mostly andesite, dacite, and diorite) that compose the Ortiz range.

The other two women's contributions were less substantial. Ada Springer, a daughter of the noted Las Vegas lawyer and crinoid specialist Frank Springer, published (1902) a short report on Pleistocene and modern snails around Las Vegas. Mildred Blodgett, about whom little is known, apparently spent a week in the field around Mt. Taylor and produced a B.S. thesis on the Cretaceous stratigraphy for M.I.T., which was later published, with the addition of paleontological information, by Shimer and Blodgett (1908).

This unfortunate underrepresentation of women in geology continued long past 1912. The first woman geologist to obtain a position at any of New Mexico's academic institutions was the noted paleontologist-stratigrapher Christina Lochman Balk, who joined New Mexico Institute of Mining and Technology and the New Mexico Bureau of Mines and Mineral Resources in the 1950s (Love 2006). It would not be until the 1970s and 1980s when significant numbers of women pursued graduate studies and were hired as geology professors in the state's academic institutions.

Geologic processes, of course, can strongly influence human societies and this was true of late territorial New Mexico. During the 25 years before statehood New Mexico experienced an unusually high frequency of earthquakes strong enough to frighten its residents. On May 3, 1887, an estimated 7.5 magnitude quake originating near Bavispe, Sonora, Mexico (about 190 miles southeast of Tucson, Arizona) was felt through much of New Mexico as far north as Las Vegas (DuBois and Smith 1980). Structural damage to buildings was reported in El Paso, but the effect in New Mexico was limited to shaking, which caused alarmed people to rush out into the streets in Las Cruces and Albuquerque. Clocks stopped, crockery fell from shelves, and a few windows were broken, but no injuries to New Mexicans resulted.

In April 1893, a series of shocks produced minor damage and much alarm in Belen, followed in July by several shocks to Albuquerque, and in September by temblors that collapsed some adobe buildings in Las Lunas and Sabinal (Northrop 1982). Two years later four quakes hit the Sabinal–Jarales area within 12 hours, causing houses to rock and household items to tumble from shelves.

Seismic activity hit a high point early in the 20th century, when the territory was struck by two separate lengthy episodes of strong earthquake swarms, centered around Socorro. The first, from January to September 1904, produced 34 shocks strong enough to be felt, although they caused no significant damage to structures or injuries to people. The second and stronger swarm occurred from July 1906 to early in 1907. The three strongest shocks averaged an estimated 6.0 in magnitude. Accurate measurement of earthquake magnitude was not possible then; it wasn't until 1960 that the first permanent seismograph station providing exact magnitudes and epicenters for New Mexico quakes was installed in the state (Northrop 1982). The 1906–1907 shocks caused substantial damage to buildings and sent frightened Socorro residents rushing into yards and streets for safety. Although no serious injuries were reported, tremors were felt nearly every day for months (see Sanford, 1963, for details). These 1906–1907 quakes were the strongest, and most numerous and sustained, shocks ever to have originated in New Mexico in its recorded history, and no earthquakes even approaching the severity of these quakes have occurred during the time New Mexico has been a state. At the time no reasonable explanation for these quakes was offered; some believed that they were somehow related to the great San Francisco quake that had occurred earlier in 1906. It was not until the 1970s, with the discovery of an ascending subsurface magma body beneath Socorro, that the high seismicity of the Socorro area was explained (e.g., Sanford 1983).

Acknowledgments

I'm grateful to the two reviewers, John Hawley and Wolf Elston, for their efforts in reading an unusually long manuscript and providing many excellent comments and suggestions that significantly improved it. Wolf and John between them have been studying the geology of New Mexico for more than a century, and in addition possess an extensive knowledge of and interest in the history of geologic studies in the state that they are always generous in sharing. Some of their comments and insights are quoted in this paper. I also thank Dave and Jane Love for contributing some valuable historical information, and my wife, Georgianna, for her good-natured assistance with the figures.

Celebrating New Mexico's Centennial

The geology of New Mexico as understood in 1912: an essay for the centennial of New Mexico statehood Part 2

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Introduction

The first part of this contribution, presented in the February 2012 issue of *New Mexico Geology*, laid the groundwork for an exploration of what geologists knew or surmised about the geology of New Mexico as the territory transitioned into statehood in 1912. Part 1 included an overview of the demographic, economic, social, cultural, and technological attributes of New Mexico and its people a century ago, and a discussion of important individuals, institutions, and areas and methods of research—the geologic environment, so to speak—that existed in the new state at that time. Here I first discuss contemporary ideas on two fundamental areas of geologic thought—the accurate dating of rocks and the movement of continents through time—that were at the beginning of paradigm shifts around 1912. Then I explore research trends and the developing state of knowledge in stratigraphy and paleontology, two disciplines of geology that were essential in understanding New Mexico's rock record (some 84% of New Mexico's surface area is covered by sediments or sedimentary rocks) and which were advancing rapidly through the first decade of the 20th century.

The geologic time scale and age of rocks

The geologic time scale familiar to geologists working in New Mexico in 1912 was not greatly different from that used by modern geologists. Darton (1916b) published the time scale in use around 1912 (Fig. 5), and it serves as a useful reference for this discussion. One difference, at least as employed by USGS geologists, was the survey practice (essentially a requirement) dating back to the early 1890s, of considering the Mississippian, Pennsylvanian, and Permian as subdivisions (series or epochs) within the Carboniferous System or Period. Many geologists outside the USGS were beginning to employ the recommendation, in Chamberlin and Salisbury's (1906) influential treatise on geology, of treating these three intervals as separate systems (or periods). The USGS did not officially adopt that position until the 1940s, long after most other geologists and state geologic surveys had.

A Paleocene Epoch is missing from Darton's time scale. Although first proposed in 1874 in Europe on the basis of fossil plants, the concept of Paleocene as the earliest major division of the Cenozoic was mainly supported by the discovery in the 1880s of primitive mammals from the San Juan Basin of New Mexico (see below, p. 26). Beds of the Nacimiento Formation containing Puercan and Torrejonian mammals typically were considered of early Eocene age through the early part of the 20th century (e.g., Matthew 1899; Gardner 1910d), but use of the term Paleocene widened as more of these early mammals were studied. By the time of New Mexico statehood these mammal faunas were being identified as Paleocene rather than early Eocene by vertebrate paleontologists (e.g., Sinclair and Granger 1914), but general acceptance of a Paleocene Epoch took longer. In the time scale presented in the most widely used American historical geology textbook of the 1920s (Schuchert 1924), for example, the term Paleocene does not appear. Instead, it refers to an "epi-Mesozoic" interval characterized by archaic mammals at the end of the Cretaceous and just before the Eocene. The USGS did not adopt the Paleocene as the earliest epoch of the Cenozoic until 1939.

Geologists studying the strata of New Mexico around 1912 were able to assign most of them accurately to the correct period or epoch based on identification of the fossils they contained. One of the outstanding problems of the late 19th and early 20th centuries, however, was determining absolute ages for the various subdivisions of the geologic time scale, and for the earth. Lord Kelvin's 1897 estimate of 20 to 40 million years for the age of the earth, based upon estimates of the age of the sun and rate of heat loss from the earth, seemed too short for many geologists. Estimates derived from geologic processes, such as the time required to account for the measured thickness of the entire sedimentary record at estimated modern rates of sediment deposition, or the time required for the oceans to attain their present salinity at measured modern rates of salt input, yielded ages that extended from Kelvin's time range to about 100 million years (see Eicher 1976, for detailed discussion). The time scale (Fig. 5) published by Darton (1916b) provides an accurate indication of the prevailing views on the age of rocks as New Mexico attained statehood. Darton assigned the Precambrian a duration of 50+ million years; the Paleozoic, 17 to 25 million years; the Mesozoic, 4 to 10 million years; and the Cenozoic 1 to 5 million years—indicating a maximum age for the earth of about 90 million years.

Although most geologists of the time were unaware of it, the theoretical and practical principles for determining accurate absolute ages for rocks were rapidly being developed in the first decade of the 20th century. Becquerel's discovery of radioactivity in 1896 led quickly to methods by which the breakdown of radioactive elements like uranium could be used to derive ages for minerals bearing that element. Rutherford and Soddy in 1902 postulated that radioactive elements decayed into other elements as radioactivity is released. Rutherford identified helium as one product of uranium decay and first made the suggestion that the age of minerals could be calculated from their helium-uranium ratios, although helium leakage was recognized as a problem. The American chemist B. B. Boltwood established in 1905 that lead was also a stable end product of uranium decay, and then (Boltwood 1907), using an approximate uranium-lead decay rate and measuring different lead/uranium ratios in minerals from rocks of different ages with the primitive analytical devices available at the time, calculated

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.

Principal Divisions of Geologic Time.[a]

[A glossary of geologic terms is given on pp. 182-185.]

Era.	Period.	Epoch.	Characteristic life.	Duration, according to various estimates.
				Millions of years.
Cenozoic (recent life).	Quaternary.	Recent. Pleistocene (Great Ice Age).	"Age of man." Animals and plants of modern types.	1 to 5.
	Tertiary.	Pliocene. Miocene. Oligocene. Eocene.	"Age of mammals." Possible first appearance of man. Rise and development of highest orders of plants.	
Mesozoic (intermediate life).	Cretaceous.	(*b*)	"Age of reptiles." Rise and culmination of huge land reptiles (dinosaurs), of shellfish with complexly partitioned coiled shells (ammonites), and of great flying reptiles. First appearance (in Jurassic) of birds and mammals; of cycads, an order of palmlike plants (in Triassic); and of angiospermous plants, among which are palms and hardwood trees (in Cretaceous).	4 to 10.
	Jurassic	(*b*)		
	Triassic.	(*b*)		
Paleozoic (old life).	Carboniferous.	Permian.	"Age of amphibians." Dominance of club mosses (lycopods) and plants of horsetail and fern types. Primitive flowering plants and earliest cone-bearing trees. Beginning of backboned land animals (land vertebrates). Insects. Animals with nautilus-like coiled shells (ammonites) and sharks abundant.	17 to 25.
		Pennsylvanian		
		Mississippian.		
	Devonian.	(*b*)	"Age of fishes." Shellfish (mollusks) also abundant. Rise of amphibians and land plants.	
	Silurian.	(*b*)	Shell-forming sea animals dominant, especially those related to the nautilus (cephalopods). Rise and culmination of the marine animals sometimes known as sea lilies (crinoids) and of giant scorpion-like crustaceans (eurypterids). Rise of fishes and of reef-building corals.	
	Ordovician.	(*b*)	Shell-forming sea animals, especially cephalopods and mollusk-like brachiopods, abundant. Culmination of the buglike marine crustaceans known as trilobites. First trace of insect life.	
	Cambrian.	(*b*)	Trilobites and brachiopods most characteristic animals. Seaweeds (algae) abundant. No trace of land animals found.	
Proterozoic (primordial life).	Algonkian.	(*b*)	First life that has left distinct record. Crustaceans, brachiopods, and seaweeds.	
	Archean.	Crystalline rocks.	No fossils found.	50 +

[a] The geologic record consists mainly of sedimentary beds - beds deposited in water. Over large areas long periods of uplift and erosion intervened between periods of deposition. Every such interruption in deposition in any area produces there what geologists term an unconformity. Many of the time divisions shown above are separated by such unconformities - that is, the dividing lines in the table represent local or widespread uplifts or depressions of the earth's surface.

[b] Epoch names omitted; in less common use than those given.

FIGURE 5—The geologic time scale in use around 1912 (redrawn from Darton 1916b).

the absolute ages for these rocks. His radiometric ages for rocks of Precambrian to Devonian age were remarkably close to those accepted today (Eicher 1976).

A year before New Mexico became a state Arthur Holmes, a student who had recently completed his undergraduate studies, published his first paper on radiometric dating (of Devonian rocks), summarizing previous work and setting down many of the basic principles that would guide radiometric dating in the future, such as the problem of sample contamination, constancy of decay rates in all environments, and the potential utility of the method in determining ages of rocks throughout geologic time. As New Mexico became a state Holmes was employed as a "demonstrator" at the Royal College of Science (now Imperial College) in London. In the lab, he was performing analyses of uranium-lead isotopic ratios that would result the following year in publication of a booklet, *The Age of the Earth* (Holmes 1913), which estimated its age at the then-unbelievably old figure of 1.6 billion years. That same year Frederick Soddy showed that radioactive elements may have more than one mass, and thus discovered isotopes, a term he coined. Recognition of isotopes in decay products of uranium, such as lead, would later allow refinement and greater accuracy in radiometric age determinations.

Research on the radioactive decay of elements had other applications to understanding earth history. The English physicist R. J. Strutt in 1906 estimated the amount of heat that radioactive minerals continuously generate within the earth's crust and established that this heat easily accounted for the measured heat flow from the earth's surface. This discovery marked the death-knell of the widespread 19th-century idea that the earth has been cooling for a long time, resulting in shrinkage of the crust and formation of various topographic and geologic features.

The technique of radiometric dating was slow to gain acceptance, and it would be interesting to know whether Darton and other geologists working in New Mexico around 1912 were aware of it. Even more than 10 years later Schuchert (1924), while mentioning radiometric dating, still gave greater consideration to geologically based estimates (now providing considerably longer age estimates), and concluded (p. 105) that geology "can therefore say that the earth since the beginning of the Archeozoic is probably at least 500,000,000 years old." Through a long career Holmes, as well as many others, continued to refine the technique and more accurately determine the ages of rocks throughout the geologic time scale. New parent-daughter decay systems were eventually added to that based on uranium and lead. Radiometric dating of rocks, however, requires both expensive analytical instruments as well as additional expenses in conducting the analyses, and so the record of absolute age determinations in the myriads of datable rock units in the U.S. increased rather slowly. The first published radiometric (K-Ar) ages for rock units in New Mexico that I have been able to find, for example, appeared in the 1963 New Mexico Geological Society guidebook (Weber and Bassett 1963; Burke et al. 1963).

Drifting continents

The concept of plate tectonics, arguably one of the two most important advances in geology in the 20th century (the other being the absolute dating of rocks), was not imagined in 1912. However, the earlier idea of continental drift, parts of which were incorporated into the broader concept of plate tectonics in the 1960s and 1970s, was first developed in the same year that New Mexico became a state. Alfred Wegener (see Wegener 1929) had received his doctorate in planetary astronomy in 1905 from Friedrich Wilhelm University (now Humboldt University) in Berlin, but was mainly conducting meteorologic research based on a 1906 expedition to Greenland while a lecturer at the University of Marburg (Germany). He began thinking about the possibility of drifting continents in 1911. In one of those amazing coincidences that makes historical research so fascinating, the 31-year-old Wegener presented his first ideas on continental drift in a talk (titled, in translation, *The geophysical basis of the evolution of the large-scale features of the earth's crust (continents and oceans)* to the Geological Association in Frankfurt on January 6, 1912, the very day New Mexico became a state.

Wegener further developed his theory, based mainly on the similar outlines of continents and the disjunct distribution of late Paleozoic fossils in Africa and South America, in two published papers later in 1912. His book, *Die Entstehung der Kontinente und Ozeane [The origin of continents and oceans]* was published in 1915, while he was recovering from wounds suffered in World War I, and it was followed by three revised editions (1920, 1922, 1929) before his untimely death in Greenland in 1930.

The concept of continental drift was almost certainly unknown to geologists working in New Mexico around the time of statehood (the first English translation of the book did not appear until the 1920s). It was not until the late 1960s, with much new evidence to support the more fundamental process of seafloor spreading, that Wegener's concept of continents breaking apart and moving away from a late Paleozoic supercontinent, and much of his evidence supporting it (although not the mechanism he proposed), was incorporated into the developing model of plate tectonics. By the 1970s plate tectonics had become widely accepted by geologists, who in subsequent decades have used it as a framework for the interpretation of many aspects of New Mexico geology.

Stratigraphy

Introduction

Geologists working in New Mexico in the 19th century had surveyed in a reconnaissance fashion many thick sequences of sedimentary rocks and had produced simple stratigraphic sections for some of them. With a few exceptions, however, definition, naming, and correlation of individual lithostratigraphic units had not been done in New Mexico, although the USGS and state geologic surveys had been routinely describing formations and groups in the East for decades. At the beginning of the 20th century detailed knowledge of New Mexico stratigraphy increased rapidly. Geologists recently arrived from the East and Midwest, such as C. L. Herrick and C. R. Keyes, began to recognize and name formations. The main thrust in understanding the stratigraphy of the territory, however, resulted from the studies of a group of exceptionally talented geologists working for the USGS that entered New Mexico in force during the first decade of the 20th century.

Below, I briefly examine the development of knowledge of New Mexico's Paleozoic, Mesozoic, and Cenozoic stratigraphy in the early years of the 20th century.

Paleozoic

Only a few brief observations of early Paleozoic strata in New Mexico were made by 19th century geologists, the most noteworthy being a report (Gilbert 1875) of "Cincinnatian" (Late Ordovician) fossils from strata (now recognized as the Montoya Group) near Silver City. At the opening of the 20th century it was generally believed that early Paleozoic strata were extremely sparse or absent in New Mexico. Studies during the first decade of the 20th

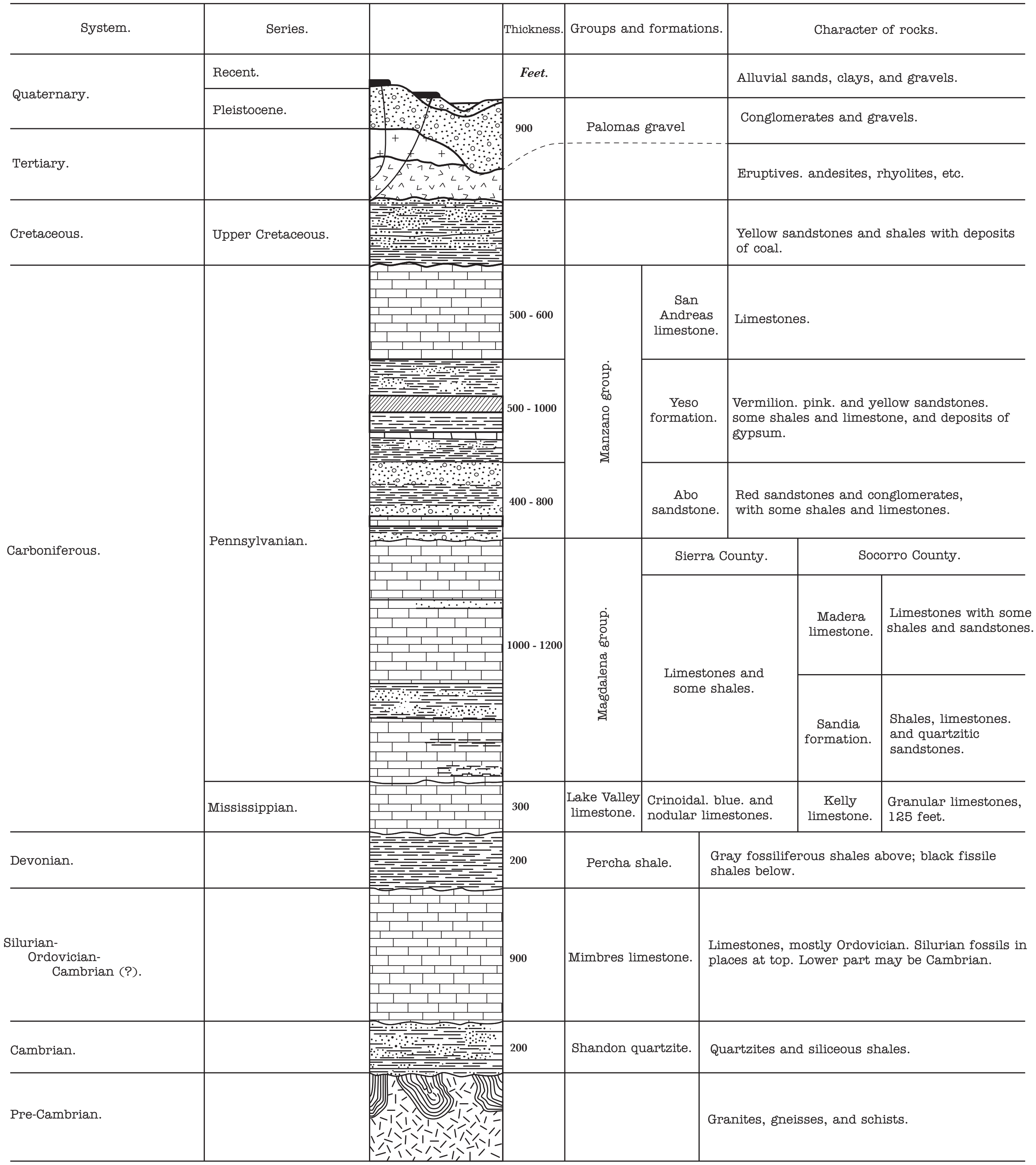

FIGURE 6—Stratigraphic units exposed in central and southern New Mexico, as understood around 1912 (redrawn from Lindgren et al. 1910). The thickness of these units is accurate for the area around the Chino mine, but the thickness of the Cenozoic volcanic section increases greatly in all directions, exceeding the combined total of all other Phanerozoic units (Elston, pers. comm., 2011).

century, however, demonstrated the presence of thick sequences of Cambrian through Devonian rocks in several areas of southern New Mexico. G. B. Richardson began work in west Texas in 1903 and published his initial observations of the stratigraphy in the El Paso, Texas, area in 1904, including description of the Paleozoic section and definition of several new stratigraphic units. Richardson viewed the Paleozoic sequence in the Franklin Mountains as consisting of (in ascending order) the Bliss (Cambrian), El Paso (Ordovician), and Hueco (believed to be Carboniferous) formations, overlain in the Guadalupe Mountains and elsewhere by Permian units he named the Delaware Mountain Formation, Capitan Limestone, Castile Formation, and Rustler Formation.

A more refined treatment of the stratigraphy of the El Paso area (Richardson 1908) restricted the El Paso to Lower Ordovician limestones, and added the name Montoya Limestone for Middle and Upper Ordovician limestone and dolomite, and Fusselman Limestone for the upper 1,000 feet of the old El Paso unit containing Silurian fossils. In this publication, and in the USGS El Paso

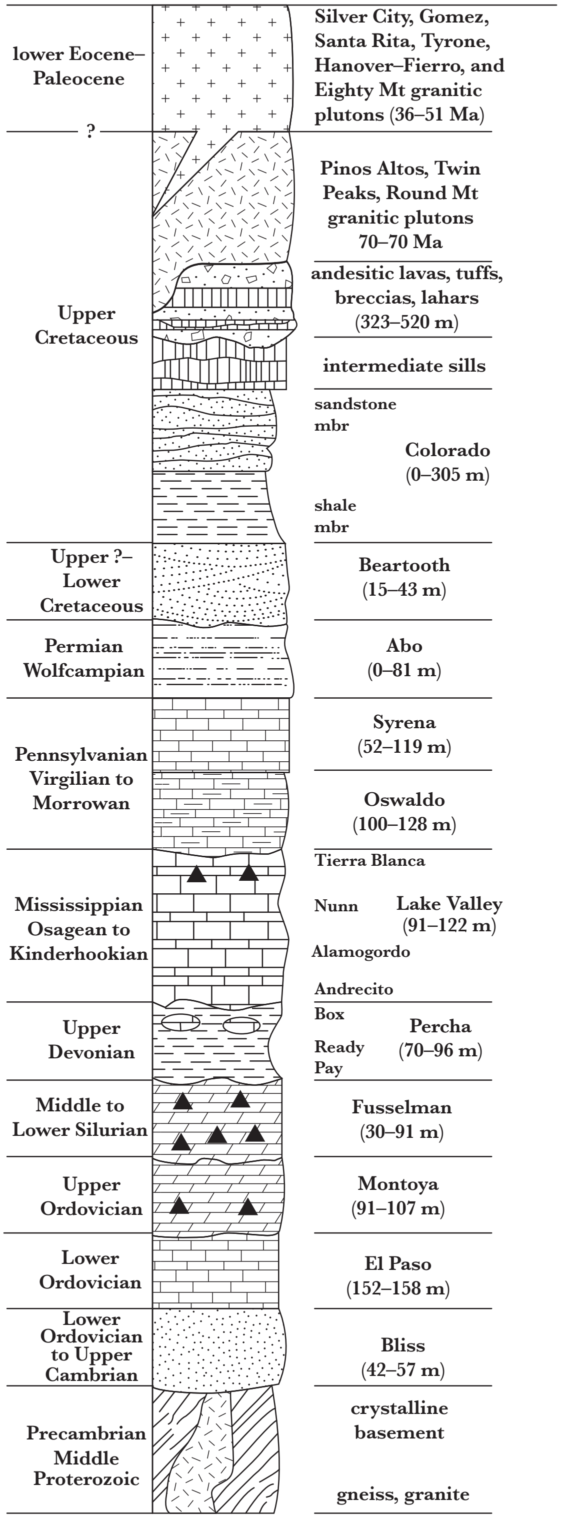

FIGURE 7—Modern stratigraphy of the Silver City area (modified from Mack et al. 2008). The Colorado Formation is a southern expression of the Mancos Shale, and the Beartooth is correlated with the Mojado or Sarten Formations by some stratigraphers.

Folio (1909) that followed, Richardson recognized no Devonian or Mississippian strata between the Fusselman and Hueco.

While Richardson was in the field in west Texas, study of the mining districts of southern New Mexico begun in 1905 soon yielded evidence of early Paleozoic strata in several mountain ranges. Gordon and Graton (1906) described Cambrian, Ordovician, Silurian, and Devonian strata in the Florida and Caballo Mountains, and in the Silver City, Santa Rita, Georgetown, Kingston, Hillsboro, and Lake Valley areas of Grant and Sierra Counties. Although the lithology and thicknesses of these strata were indicated, no formational names were applied.

A few months later, Gordon and Graton (1907) introduced the terms Shandon Quartzite (Cambrian), Mimbres Limestone (Ordovician and Silurian), and Percha Shale for the presumably Devonian dark-gray shales overlying the Silurian limestones, which were not present in west Texas. Study of the fossils from the Percha (Kindle 1909) soon verified the Late Devonian age of this formation. Lee (1908) provided more detail on the stratigraphy and paleontology of this sequence in the Caballo Mountains, although without adopting formational names. By 1910, in the final report of the ore deposits study, Gordon (in Lindgren et al. 1910, pp. 225–228) provided extended descriptions of the Cambrian through Devonian strata in southern New Mexico, using the names noted above. He recognized (p. 227) that Richardson's units defined in the Franklin Mountains might be extended into New Mexico with further study.

Meanwhile, by 1910 Darton had begun geologic studies of Luna County. His first publication (Darton and Burchard 1911) on this area of southern New Mexico briefly reported early Paleozoic strata, without applying formation names. Thus, by 1912 the stratigraphy, including lithology and thicknesses, of the Cambrian through Devonian sequence in parts of southern New Mexico (Fig. 6) was reasonably well known, and the Shandon/Mimbres/Percha terminology for these strata was current, although tentative. If someone had asked Darton during the summer of 1912 what he thought, however, probably he would have considered Richardson's formational names to be more appropriate for the Cambrian to Silurian part of the New Mexico early Paleozoic sequence. In Darton's (1916a) final report on the geology of Luna County, the lower Paleozoic sequence consists of the Bliss, El Paso, Montoya, Fusselman, and Percha formations, and by the following year (Darton 1917a) he had correlated these units widely across southern New Mexico, from the Silver City area to the Sacramento Mountains. These formational names, with some subsequent refinements (several Devonian formations are now recognized in addition to the Percha), have been used ever since (Fig. 7).

Profusely fossiliferous Lower Mississippian limestones had been recognized around the Lake Valley silver mines since the early 1880s (e.g., Springer 1884; see Kues 1986 for a detailed historical summary), and from the time of their discovery had been called the Lake Valley Limestone. Gordon (1907a) reviewed the stratigraphy, thicknesses, and paleontology of the Lake Valley at several locations in Sierra County, and the formation was well established by 1912. Interestingly, Gordon (1907a, p. 58) stated in a footnote that a "bulletin of the U.S. Geological Survey treating of the fauna of the Lake Valley formations [sic] is now in preparation by Dr. [George H.] Girty." Girty apparently never completed or published his work on the Lake Valley fauna, which is unfortunate, as most elements of the profuse Lake Valley fauna, even its famous crinoids, have not been comprehensively studied to this day. The stratigraphy of the Lake Valley sequence as recognized in the early 20th century has been considerably refined since the 1940s with the addition of an underlying formation (Caballero) and several members of the Lake Valley Formation.

Lower Mississippian strata were also known questionably (because of lack of fossils) in the San Andres and Caballo Mountains and definitely in the Sacramentos (many fossils, including crinoidal limestones) as a result of C. L. Herrick's reconnaissance surveys (Herrick 1900b, pp. 117, 119); these later proved to be additional exposures of the Lake Valley Limestone. Herrick (1904a) had also suggested a Mississippian age for what he named the Graphic–Kelly formation—the limestones that hosted the important lead-zinc orebodies mined in the Kelly (Magdalena) area of Socorro County. Gordon (1907a) had little to add, but shortened the stratigraphic name to Kelly Limestone, which eventually did yield Mississippian fossils, and noted possible Mississippian exposures in the Ladron Mountains, discovered by Lee in 1905.

By 1912 geologists were reasonably certain that exposures of Cambrian through Mississippian strata were confined to southern New Mexico. The explanation given (e.g., Lindgren et al. 1910,

p. 30) was that northern New Mexico was a land area during much of the Paleozoic, until covered for the first time by Pennsylvanian seas. The alternate view, that sediments were deposited during the early and middle Paleozoic but eroded away during some interval between the Mississippian and Pennsylvanian, was considered unlikely, “as so extensive a removal would hardly have been effected without some evidence of structural unconformity between the two principal divisions of the Carboniferous.” Mississippian exposures were later discovered and studied in several areas of northern New Mexico beginning in the 1950s, but 100 years after statehood no pre-Mississippian Paleozoic exposures have been recognized, although of course early and middle Paleozoic strata are known in the subsurface. Clearly, contra Lindgren et al. (1910), marine environments covered northern New Mexico many times before the Pennsylvanian, and some of these strata are preserved.

In contrast to early and middle Paleozoic strata, 19th century geologists encountered extensive exposures of Pennsylvanian strata in New Mexico, both in the northern (Sangre de Cristo, Jemez, Sandia–Manzano ranges) and southern (San Andres, Caballo ranges) parts of the territory. In part because of the great thickness of some sections, knowledge of Pennsylvanian stratigraphy was generalized, with no attempt to define lithostratigraphic units. In addition, although Permian strata were also identified in the 1850s in the Guadalupe Mountains, in most areas strata later identified as Permian were typically considered part of Upper Carboniferous sequences. Much more detailed study of the territory’s Pennsylvanian and Permian stratigraphy began around the turn of the 20th century, and by 1912 the main framework of New Mexico’s late Paleozoic stratigraphy had been established.

The first modern studies of New Mexico’s late Paleozoic strata were largely the result of a brief but intensive period of activity by C. L. Herrick, who examined late Paleozoic exposures in the Sandia and Manzano Mountains near Albuquerque, Mesa Lucero, the ranges around Socorro, and in the Oscura, San Andres, Caballo, and Sacramento Mountains. Briefly, Herrick (1900b) recognized in the Sandias and Manzanos the broad outlines of the major subdivisions of Pennsylvanian and Permian stratigraphy in central New Mexico, including, in ascending order, a basal Pennsylvanian clastic unit (named the “Sandia series”) above the crystalline basement, a thick interval of limestone (unnamed), a sequence of interbedded red sandstones and thin limestones (named the “Manzano series”), clastic red beds, and finally a thick sequence of brown, red, and gray clastics, evaporites, and limestone that he thought (incorrectly) might be Mesozoic. On the basis of fossil collections, the “Manzano Series” was considered to be Permo–Carboniferous in age. In the Sacramento Mountains, Herrick observed thick Pennsylvanian limestones resting upon Mississippian strata, and overlain by Permo–Carboniferous interbedded red clastics and limestone (the Laborcita Formation of present usage), which in turn were overlain by gypsum, limestone, and brown and red clastic beds.

At about this same time Charles R. Keyes also began to publish on Paleozoic stratigraphy, coining many names for stratigraphic units. However, because his stratigraphic information apparently was derived from the work of others, such as Herrick, rather than his own observations, because his stratigraphic names were not adequately defined or related to actual rock sections, and because he was inconsistent and contradictory in the use of his names, the writings of Keyes were quickly ignored by other workers. His only lasting contribution to the development of late Paleozoic stratigraphic nomenclature was introduction of the name Madera Limestone (Keyes 1903) for the thick carbonate-dominated sequence above the Sandia Formation in the Sandia and Manzano Mountains, which Herrick had briefly described but not named.

During his geologic reconnaissance of New Mexico mining districts Gordon also studied the Pennsylvanian part of the section in the mountains along the Rio Grande south of the Sandias. Gordon (1907b) evaluated the rather vague, and in Keyes’ case contradictory nomenclature that had been applied to Pennsylvanian strata and established a simple and workable set of names—a lower mainly clastic interval (Sandia Formation) overlain by the Madera Limestone, with both combined as the Magdalena Group. He also proposed the term Manzano Group for the mostly nonmarine clastics and evaporites that Herrick had noted above the Madera interval. Based on rudimentary knowledge of the fossils, the Magdalena Group was believed to represent the lower part of the Pennsylvanian and the Manzano Group the upper part.

W. T. Lee was also studying the thick late Paleozoic sequences near the Rio Grande, focusing on the red beds and other units of the Manzano Group. He assembled his preliminary observations in a paper (Lee 1907a) that described the red-bed sequences of central and southern New Mexico as typically consisting of a lower, dark-red sandstone marked by a basal conglomerate, a middle division of shale, gypsum, and minor limestone, and an upper unit of yellow, pink, and white sandstone and shale, overlain in the south by a thick, fossiliferous limestone. Fossils seemed to indicate a Carboniferous age. Lee was careful to state that no part of this distinctive sequence could be assigned to the Triassic, which also featured red beds in New Mexico, and noted that a red-bed sequence in the Elephant Butte area, which possibly could be confused with the Carboniferous red beds, was of Cretaceous age based on plant and dinosaur fossils (the McRae Formation of modern usage).

These stratigraphic studies by Lee, and the studies by Girty of the fossils he collected, resulted in an important USGS bulletin (Lee and Girty 1909) in which Lee established the lower part of the Manzano Group as the Abo, the middle part as the Yeso, and the overlying limestone as the San Andres formations. Girty considered the Manzano Group to be at least in part equivalent to the Hueco Limestone and older than the Guadalupian strata he and Richardson had been studying in west Texas and southern New Mexico. Both of those observations were correct, but his suggestion that the Manzano was also equivalent to the Whitehorse and Quartermaster beds of Texas and Oklahoma was off; the latter formations are considerably younger. Girty reckoned the Manzano faunas to be older than the classical Permian faunas of Russia (and thus Pennsylvanian in age). However, continuing study of the Permian strata to the south (see below), and recognition of an unconformity between the Magdalena and Manzano Groups suggesting regional diastrophism (Lee 1917a), soon made a Permian age for the Abo–Yeso–San Andres sequence preferred. Use of the term Manzano Group faded rapidly, and with recognition of the Permian age of the Manzano formations, the underlying Magdalena Group came to represent the entire Pennsylvanian in New Mexico, a situation that made that name unnecessary as well.

Despite some difficulties with its age and correlation, the work of Lee and Girty on the Manzano Group strata represents an important early contribution to knowledge of New Mexico late Paleozoic stratigraphy. Lee’s skill in field reconnaissance across great distances under primitive conditions, and in synthesizing observations on a 2,000+ foot-thick sequence of locally heterogeneous and often incompletely exposed strata is impressive. His perspicacity in recognizing formation-rank units in this thick sequence is indicated by the fact that the Abo, Yeso, and San Andres formations were widely used by subsequent workers, and today occupy large areas on modern geologic maps of the state.

To the south, in and around the Guadalupe Mountains, USGS paleontologist George Girty (Fig. 8) began to examine the thick, late Paleozoic strata of this range in 1901, and George Richardson, also of the USGS, began field work in Trans-Pecos Texas in 1903. The details of their stratigraphic studies in southeastern New Mexico were discussed by Kues (2006) and are only briefly summarized here. Girty’s studies of the thick limestones along the crest of the southern end of the Guadalupes (Girty 1902, 1905, and especially his 1908 monograph) indicated that the faunas were unique and of Permian, probably Late Permian, age. Richardson (1904) coined the name Capitan Limestone for these limestones, and Delaware Mountain Formation for the underlying clastic units (now divided into many formations and known to be deposits of the Delaware Basin adjacent to the Capitan Limestone). He also recognized the “Castile gypsum” as possibly overlying the other two formations, and he named the Rustler Formation for limestones and sandstones above the Castile. All of these formations were identified as Permian, and considerably younger than the underlying Hueco Formation (also named by Richardson) and believed to be Carboniferous in age (it is actually Early Permian).

FIGURE 8—George H. Girty, USGS (Williams 1940).

Although the studies of Girty and Richardson began in west Texas, the strata they observed were soon traced into southeastern New Mexico, in order to determine what became of the Guadalupian units to the north and northeast. Girty (1909) made the important observation that the thick Capitan Limestone becomes thin-bedded limestone and sandstone to the north, and ultimately grades into unfossiliferous red beds (Artesia Group of present usage). Examination of the stratigraphy of the Sacramento Mountains led Girty to correctly correlate part of the Hueco Limestone with his Manzano Group (both considered Pennsylvanian rather than Permian, as later work would show). However, he believed that the limestone capping the Sacramento Mountains near Cloudcroft was Hueco (it is actually San Andres) and therefore failed to realize that there are actually two red-bed sequences in the Permian in this region, the upper one (the present Artesia Group, the backreef facies of the Capitan Limestone), separated from the lower one (Abo Formation, in part equivalent to the Hueco) by the Yeso–San Andres limestones and evaporites. He did correctly note that the strata initially studied by Herrick below the red beds along the western front of the Sacramentos (the present Holder and Laborcita Formations) were of Pennsylvanian age, based on their fossils. In concert with Richardson's study (1910) of the Permian strata east of the Guadalupe Mountains, along the Pecos River valley, Girty did recognize that the youngest Permian red beds in this area (e.g., Rustler Formation) postdated Capitan and Castile deposition. Thus, although all of the details of correlation of Permian strata from the Guadalupe to the Sacramento and San Andres Mountains were not completely worked out by 1912, geologists had a general concept of the age and lithostratigraphic relationships of this thick sequence across the large area of southeastern New Mexico. More precise and accurate correlations followed through the next 20+ years, with interpretation of the Capitan and associated strata as representing a gigantic reef complex appearing in 1929.

In west-central New Mexico Dutton (1885) had concluded that most of the thick sequence of late Paleozoic strata resting on Precambrian basement around the Zuni Mountains was of Late Carboniferous age ("Aubrey Group"), capped by a thinner unit he regarded as Permian. Darton (1910) called this latter unit the Moenkopi and considered the underlying thick, mainly limestone unit as "undifferentiated Pennsylvanian" (Lucas 2003, fig. 8). Later studies showed nearly all of the "undifferentiated Pennsylvanian" to be Permian (Abo, Yeso, Glorieta, San Andres Formations of modern usage), and the "Permian" strata to be of early Late Triassic age, immediately underlying the Chinle Group of Gregory (1916, 1917) (see Fig. 9 for evolution of nomenclature).

Mesozoic

Triassic, Jurassic, and Cretaceous strata had all been identified in New Mexico by the early geologist-explorers in the 1850s. Triassic red beds had been recognized initially (although not without controversy) by lithology and stratigraphic position in several areas of northern and central New Mexico, and their Triassic age was verified by vertebrate fossils first studied by Cope in the 1870s, and by plant fossils in Petrified Forest (northeastern Arizona) and in north-central New Mexico. Detailed stratigraphic study and division into named formations in most areas had not been accomplished by the turn of the century.

In the Zuni Plateau region of northwest-central New Mexico, Dutton (1885) recognized as Triassic a thick sequence of mostly red shales (unnamed), overlain by a thinner cliff-forming sandstone that he called Wingate Sandstone (now known to be the Jurassic Entrada Sandstone; see Lucas, 2003, for a detailed discussion of Dutton's stratigraphy).

By the time of statehood, Darton (Fig. 10) had published a reconnaissance geologic study of northwest and north-central New Mexico (1910), accompanied by what was one of the most detailed geologic maps of any part of the state at that time. This map extended from the Jemez Mountains and Albuquerque areas westward into Arizona, between the latitudes of Gallinas in the north and Los Lunas in the south, an area of more than 15,000 square miles in New Mexico (plus a larger area of Arizona). Darton mapped large areas of "undifferentiated Triassic" in the area west of Los Lunas to south of Laguna; around the east, north, and west margins of the Zuni Mountains, and around Zuni Pueblo, with smaller areas present along the west and southeast sides of the Nacimiento Mountains. These strata include much of what later became the Chinle Formation (called the "Leroux Formation" by Darton), as well as the overlying Wingate and Zuni Sandstones, which Darton believed could be either Triassic or Jurassic, noting (p. 51) that there was no direct evidence of Jurassic strata in the region. In many areas this "undifferentiated Triassic" rested upon the Moencopie [sic] Formation, 500+ feet of reddish sandstones and shales with petrified wood, which Darton believed to be Permian but which is now known to be Late Triassic (see Fig. 9). The Zuni Sandstone was in turn overlain by the Cretaceous Dakota Sandstone, Mancos Shale, and Mesaverde Formation ("undifferentiated Cretaceous" on the map).

Darton's 1910 study is useful as a status report on the geology of northwest New Mexico but also illustrated that much remained to be done in accurately understanding and dating the pre-Cretaceous stratigraphy in this area. The USGS was aware of this, and in 1909 sent Herbert E. Gregory to begin field work in the "Navajo country" to the north. His work culminated in two monographs (Gregory 1916, 1917) that would greatly increase understanding of the Triassic and Jurassic stratigraphy of northwestern New Mexico, and, among other terms, introduced the name Chinle Formation for the thick sequences of Upper Triassic red beds that previous investigators had noted all over northern New Mexico, and the name Todilto Formation for a widespread Jurassic limestone/gypsum unit.

As an aside, mention must be made of a series of USGS guidebooks to the western U.S., along major railroads, begun in the mid-'teens. These were designed to inform and educate the increasing numbers of Americans who were traveling west on the main railroads so that they could fulfill their patriotic obligation to "know America first" and to "appreciate keenly the real value of the country." The third guidebook in this series was the Santa Fe route, with a side trip to the Grand Canyon, which Darton (1916b) wrote. Beginning in Kansas City and following the AT&SF westward through New Mexico to Los Angeles (in New Mexico the route is nearly that of I–25 from Raton to Albuquerque, and I–40 from Albuquerque to the Arizona state line), this guidebook provided geographic, geologic, archaeologic, historic, cultural, vegetational, and hydrologic information continuously along the route (rather similar to modern New Mexico Geological Society guidebook road logs), and it included detailed geologic and topographic maps for the entire distance. Although not a

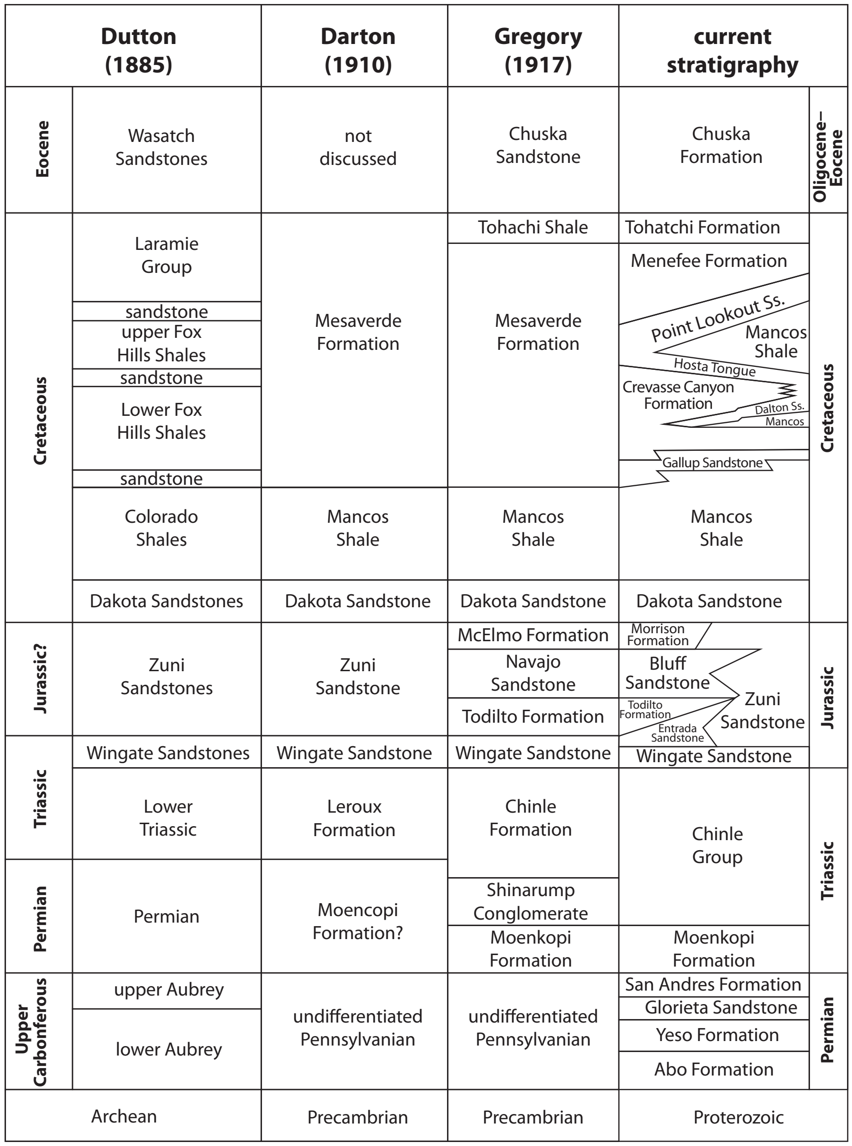

FIGURE 9—Dutton's (1885) stratigraphy of west-central New Mexico, and revisions to the present (modified from Lucas 2003, fig. 8).

source of new geologic information or interpretation, Darton's (1916b) guide book rewards the modern reader with its detailed and multifaceted portrayal of New Mexico as it existed shortly after statehood was attained, along the main route through which visitors entered, passed through, and viewed New Mexico.

Triassic red beds, in places with fragmentary vertebrate, unionid bivalve, and plant fossils, had long been known in other parts of New Mexico, such as the Nacimiento Mountains, near Abiquiu, and especially in east-central New Mexico (Tucumcari area) and along the Pecos River to the south. In Texas, correlative strata had been named the Dockum Group (with lower Tecovas and overlying Trujillo Formations) in the 1890s, and it was generally recognized that the same units could be traced across the neighboring New Mexico Great Plains region, although the stratigraphic names had not been formally applied to New Mexico exposures. As time went on, the tendency of New Mexico geologists has been to assign these units to the Chinle Formation (or Group), extending the concept of that unit far eastward from the San Juan Basin. Texas geologists continue to refer these Triassic units to the Dockum Group (see Lehman 1994, for detailed discussion).

Elsewhere in New Mexico some of Willis Lee's first geologic work traced the Morrison Formation (by then famous for its remarkable dinosaur fossils in Colorado, Utah, and Wyoming) southward from Colorado into northeastern New Mexico, and coined the name Exeter Sandstone (now recognized as an eastern expression of the Entrada Sandstone) for a thin unit below the Morrison (Lee 1902). Lee and Darton at that time believed that the Morrison could be traced laterally southeastward into shales bearing Comanchean (Early Cretaceous) marine fossils. Stanton (1905) provided a regional discussion of the Morrison, noted a few fragmentary dinosaur bones in outcrops near the Canadian and Dry Cimarron Rivers of New Mexico, and demonstrated that the fossil-bearing late Comanchean beds were stratigraphically above the Morrison. However, the age of the Morrison could not be firmly established; it could still be Early Cretaceous, Jurassic, or span both times. A subject of debate for several following decades, the Morrison is now recognized to be mainly or entirely of Late Jurassic age (Lucas 2004).

By the first decade of the 20th century, the stratigraphy of the Cretaceous Period in New Mexico had been more intensively studied and finely divided into formation-rank units than either the Triassic or Jurassic sequences. This was largely a consequence of much more extensive Cretaceous outcrops and the fact that much of the Cretaceous section was marine and profusely fossiliferous, allowing subdivisions of the Cretaceous to be readily recognized on the basis of index fossils and correlated with the comparatively well-studied stratigraphy of the vast Cretaceous exposures across the midwestern and western U.S. Virtually all Cretaceous strata in

FIGURE 10—N. H. Darton, USGS (King 1949).

New Mexico were known to be of Late Cretaceous age. The only exceptions were fossiliferous outcrops in the Tucumcari area that had been studied in the 1890s and securely dated as late Early Cretaceous in age (see Kues 1985b for details), and exposures of the same age in extreme northeastern New Mexico and near El Paso.

Nineteenth century geologists had identified large areas of Cretaceous exposures across northern and central New Mexico, and some generalized stratigraphic sections, together with their fossils, had been documented. At this time several broad regional Late Cretaceous units, often referred to as groups, had been generally accepted by stratigraphers, including in ascending order, Dakota, Colorado, Montana (including Fox Hills), and Laramie. New Mexico Cretaceous strata usually could be assigned to these units based on their fossil content. Efforts to subdivide these units in more detail gathered force in the 1890s, and by 1912 many formations familiar to modern geologists had been recognized in New Mexico, many having been extended into the territory from Colorado. The first two local Cretaceous units identified in New Mexico were named by Herrick (1900a), based on his reconnaissance study of northern Socorro County. These two sandstone units—Tres Hermanos and Punta de la Mesa—were within thick, predominantly shaly, Colorado-age sequences. Of these names, the Tres Hermanos is still in use, whereas the Punta de la Mesa is now regarded as part of the Gallup Sandstone (see Hook et al. 1983, for discussion).

The main impetus behind a major USGS effort to study the Late Cretaceous stratigraphy of New Mexico was to better understand the geologic occurrences of coal. Although coal had been mined and used in New Mexico for centuries, the coming of the railroads to the territory in 1878–1882 stimulated a great increase in coal mining, mostly to power steam locomotives, for smelting of metallic ores, and for space heating in buildings. By 1900 nearly 1.5 million tons of coal per year (increasing to 3.5 million tons in 1912) were being mined in New Mexico (Kottlowski 1965). In addition, by 1900 coal was by far the most valuable geologic resource in the United States (Campbell 1906). In order to better understand the geologic occurrence of this essential resource, and therefore to better locate new deposits and more efficiently (and cheaply) exploit them, Congress in 1904 appropriated funds to the USGS for the study of the country's coal deposits, with special attention to the rapidly developing coal fields of the West. The survey's efforts in New Mexico began in 1905, with the goal of "determining the areal distribution of the coals, correlating the beds worked at various points, and determining the geological horizons at which this coal occurs" (Campbell 1906, p. 204). In New Mexico at this time, little detailed information was known, beyond the general observation that most of the territory's coal deposits appeared to be in strata of Cretaceous age. Considerable advances in knowledge of Cretaceous stratigraphy, depositional environments, facies relationships, and paleontology resulted from the USGS's studies of the coal-bearing and related strata in New Mexico.

Storrs (1902) surveyed the coal fields of the Rocky Mountains, including those being worked or known of in New Mexico—the Raton, La Plata, Mt. Taylor, Gallup, Cerrillos, Tejon (Hagan Basin), Jarillosa, Carthage, White Oaks, Mora County, and Gila River (northern Grant County) fields. He provided little information about each field, typically limited to a vague indication of stratigraphic position, number of producing beds, dip of the beds, and brief remarks on the grade of coal being mined. His survey illustrated how little was known of the geology of the territory's coal fields at this time.

The major thrusts of the USGS coal studies were the San Juan and Raton Basins, where most of the territory's coal was being mined, but survey geologists also visited and studied many lesser-producing areas. The first publication on this research was a brief account of the coal field near Engle, south of the Fra Cristobal range, by Lee (1906), who would become a central figure in studies of Cretaceous stratigraphy in New Mexico (see below).

Work on the San Juan Basin began in 1905, and Schrader (1906) recorded the results of his reconnaissance survey of what was then called the Durango–Gallup coal field. A simple geologic map displayed the Cretaceous strata around the margins of the basin, but the central San Juan Basin was a large geologically blank space on his map. The stratigraphy of the coal-bearing Cretaceous strata was very generalized. The Mesaverde and "Laramie" (Fruitland and Kirtland Formations of modern usage) units extended from Durango southward to Dulce and Monero and along the west side of the Nacimiento Mountains. From Cuba around the south side of the basin to Gallup, the coal-bearing units were identified as the Colorado and lower and upper Montana Groups (together representing most of Late Cretaceous time). The relationship between the Mesaverde and Montana Groups was then unknown. Although his descriptions of the geology of these districts were not extensive, Schrader's report significantly increased the stratigraphic information available for the margins of the San Juan Basin.

Reconnaissance field work continued in 1906, and the results were published by Shaler (1907). This report focused on the western part of the basin, from Durango to Gallup, and provided a more detailed and complete geologic map of this area than had been published by Schrader. It also considerably refined the Cretaceous stratigraphy, with Shaler extending several formation names first established or recognized by Whitman Cross (1899) in southwestern Colorado southward into New Mexico. Broad general units like Colorado and Montana disappeared; Shaler's section consisted of (in ascending order) Dakota, Mancos, Mesaverde (consisting of two massive sandstones with a coal-bearing shale/thin sandstone unit in the middle), Lewis, and "Laramie" (with a massive sandstone at its base) formations. The post-"Laramie" Animas Formation was noted in Colorado, overlain by "Eocene" strata, including the Puerco marl and Wasatch(?) formations. This is the framework of the modern San Juan Basin stratigraphic section, although some name changes and new formations and members were added later.

Contributions during the next few years included brief reports of smaller coal fields in New Mexico (e.g., Campbell, 1907a, on the Una del Gato field, including the Hagan Basin, and Campbell, 1907b, on the coal around Fort Stanton, Lincoln County), and more focused studies of smaller areas of the San Juan Basin. Field work undertaken in 1907 resulted in three reports by James H. Gardner. Gardner (1909a) described the coal-bearing Cretaceous strata near Gallina and Raton Spring (Pueblo Pintada) around the southeastern side of the basin, recognizing the Dakota, Mancos, Mesaverde, Lewis, and "Laramie" formations, separated by a significant unconformity from the overlying early Cenozoic Puerco, Torrejon, and Wasatch formations. Although lacking coal deposits, the early Cenozoic beds in the basin interested Gardner more than previous and most subsequent USGS geologists (see further discussion below). He then

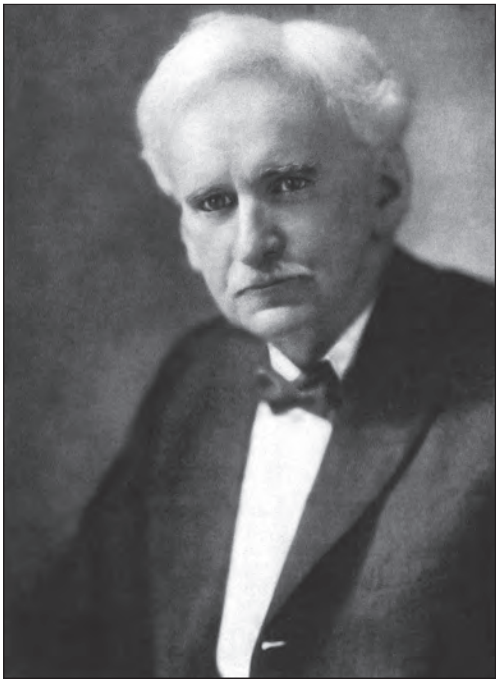

FIGURE 11—Willis T. Lee, USGS (Alden 1926).

examined the Durango to Monero coal field on the north side of the basin (Gardner 1909b), reporting in detail on the local coal beds in the Mesaverde and "Laramie" formations, and moved (Gardner 1909c) to the area around Gallup eastward to San Mateo, mapping the distribution of upper Mancos and Mesaverde strata.

Gardner's field work in 1908 resulted in reports of isolated coal fields in Santa Fe and San Miguel Counties (Gardner 1910a), near Carthage, in Socorro County (Gardner 1910b), and between San Mateo and Cuba (Gardner 1910c). The first of these papers included mention of a thin coal bed in Pennsylvanian strata north of Pecos, one of only a few reports of Pennsylvanian coal in New Mexico; the coal was characterized as being too thin and poor in quality to be of commercial value. In contrast, coal had been mined in the Carthage area since 1861, yet was far south of the San Juan Basin, so the local geology was studied in some detail, and Gardner included a geologic map and an accurate stratigraphic section. He determined that the coal was coming from Montana-age Late Cretaceous strata, believed to correspond "closely if not exactly with the Mesaverde Formation of the San Juan Basin" (Gardner 1910b, p. 161). The coal-bearing units are in the Crevasse Canyon Formation (Mesaverde Group) and in strata overlying the Cretaceous, assigned to the post-Wasatch Eocene by Gardner, known today as the Baca Formation.

Gardner's final field observations of 1908 (Gardner 1910c) were in the area from Cuba south and westward to San Mateo, part of which had been sketchily mapped by Schrader (1906). Gardner produced a more detailed map and stratigraphic analysis. Where Schrader (1906) had mapped only a narrow zone of "upper Montana coal group" strata around the periphery of this area, Gardner was able to identify these strata as Mesaverde Group, exposed in a wide area between the Mt. Taylor volcanic field and the band of "Laramie" and early Cenozoic formations in the Pueblo Alto/Pueblo Pintada area to the north. He also noted a massive sandstone at the base of the earliest Cenozoic Puerco Formation, which would eventually receive the name of Ojo Alamo Sandstone. Some discussion of the "powerful erosion" that produced the high mesas "at some time previous to the Pleistocene and subsequent to the Eocene" (p. 171) was included, as well as brief descriptions of the Mt. Taylor volcanic field, the Rio Puerco "volcanic plugs," and the younger lava flows in the valley of the Rio San Jose. Gardner (1910d) also published a study of Paleocene strata in the San Juan Basin (see Cenozoic section, p. 23) to conclude a very productive series of studies on San Juan Basin stratigraphy.

Continuation and expansion of USGS studies of coal-bearing and related Cretaceous strata in northern New Mexico continued throughout the decade of 1910–1920. The preeminent figure in these studies was Willis Lee (Fig. 11), noted earlier for his contributions to the late Paleozoic and Jurassic stratigraphy of New Mexico. Lee (1864–1926) was born on a farm in Pennsylvania, entered Weslayan University, Connecticut, at the advanced age of 26 and graduated in 1894 (biographical information from Alden 1926). He was a professor of geology at Denver University for a few years, then (1898–1900) pursued a master's degree at the University of Chicago, following which he lived in Trinidad, Colorado, and was principal of that town's high school. In 1902 Lee entered the doctoral program at Johns Hopkins, but an attack of typhoid the following year forced him to leave school (he later finished the doctorate in 1912).

While in Trinidad and at Johns Hopkins he published two papers on New Mexico geology, the first on the Jurassic (see above, p. 19), and the other a study of the canyons of northeastern New Mexico (1903). In mid-1903, after recovering from typhoid, Lee was offered a job in the newly organized western section of the hydrographic branch of the USGS, as a field assistant to N. H. Darton. He was initially stationed in Phoenix, Arizona, where he studied the geology and ground water resources of the Gila, Salt, and Colorado River valleys and of the Owens Valley in California. In 1904 and 1905 in worked in New Mexico as well, studying the water resources of the Rio Grande valley, resulting in a lengthy publication (Lee 1907b). Lee used his time in the Rio Grande valley to explore and observe the geology of adjacent areas, which resulted in several important publications on Paleozoic stratigraphy (see Paleozoic section, pp. 14–18). One senses that Lee was a lot more interested in geology than in water resources.

In 1906 Lee was transferred from the hydrographic division to the survey's coal fields study, and by 1907 he was beginning to study the stratigraphy and coal of the Raton area. Coal had been observed around Raton Pass by the earliest American explorers in New Mexico, and Raton had been a center of coal mining since the 1880s. Lee (1909) outlined his initial observations on the stratigraphy of the Raton area, which included (in ascending order) the Jurassic Morrison Formation, Upper Cretaceous Dakota, Benton, Niobrara, Pierre, and Trinidad formations, and two coal-bearing units separated by a newly discovered unconformity. Previously, these two units had been grouped within the "Laramie" (= latest Cretaceous) Formation, but Lee traced the unconformity widely around the Raton field, and with paleobotanical data from Knowlton, maintained that the lower unit was of pre-Laramie age (equivalent to the Mesaverde Group in the San Juan Basin) and the thick sandstone above the unconformity was of post-Laramie (early Tertiary) age. Lee (1913b) later applied the name Vermejo Formation to the lower unit and Raton Formation to the upper. The discovery of this unconformity was considered of great importance at the time, but future work would show that it did not represent a lengthy gap in the record at the Cretaceous–Tertiary boundary, nor did it even occur exactly at this boundary.

It did not take Lee long to realize that in order to properly assess the Cretaceous and early Cenozoic stratigraphy of the Raton Basin he needed to correlate it with the stratigraphy of the San Juan Basin and with the marginal small coal fields in central and northwestern New Mexico where most of the survey's efforts thus far had been focused. However, as Lee (1912a) noted, the Cretaceous strata of the Raton and San Juan Basins were on opposite sides of the southern Rocky Mountains, and none of the Cretaceous strata extend continuously around the mountains. Further, he wanted to find in the San Juan Basin the large Cretaceous–Tertiary unconformity he thought he had identified in the Raton area.

Thus, Lee spent the 1911 field season re-examining the stratigraphy of the San Juan Basin and smaller isolated coal fields, as well as intervening areas that had not been studied previously. With more detailed stratigraphic data, coupled with large fossil collections (invertebrates identified by Stanton and plants by Knowlton)

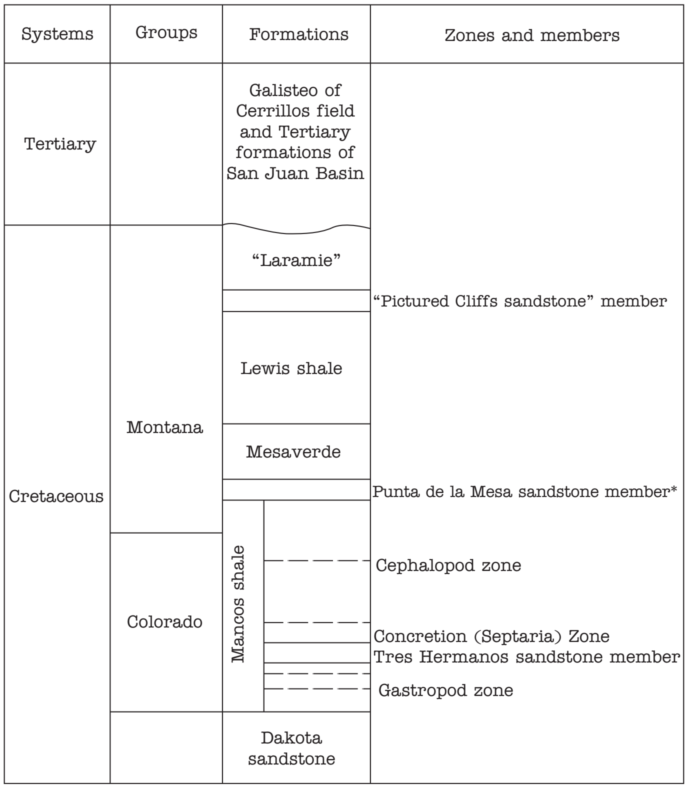

FIGURE 12—Upper Cretaceous stratigraphic units recognized in 1912 (redrawn from Lee 1912a).

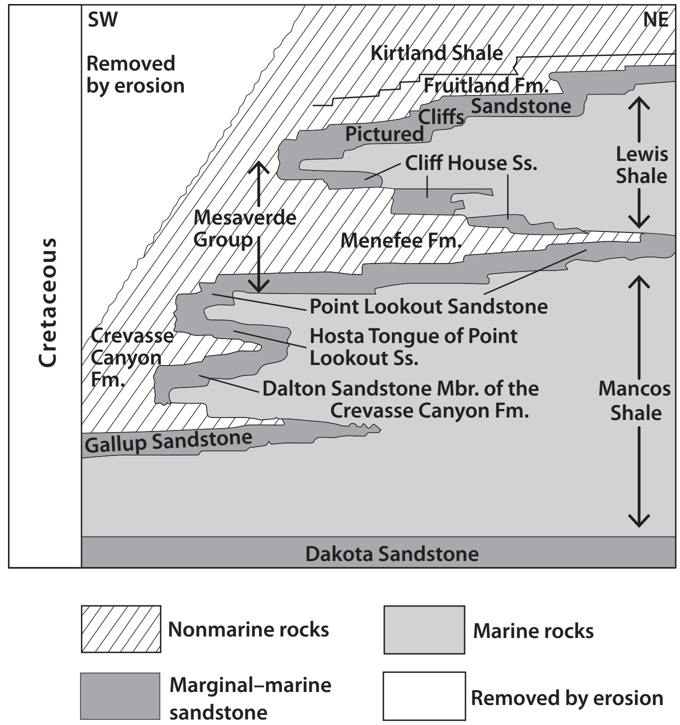

FIGURE 13—Generalized modern Late Cretaceous stratigraphy of the San Juan Basin (modified from Wright Dunbar et al. 1992), showing transgressive-regressive nature of the stratigraphic units, which would begin to be recognized soon after New Mexico became a state.

that made possible more refined age determinations, Lee (1912a) produced a lengthy paper tying together the largely isolated observations of his predecessors into an integrated regional synthesis of Cretaceous and early Cenozoic stratigraphy across central and northwestern New Mexico, and he was able to tentatively correlate some parts of this section with the section in the Raton area.

The Upper Cretaceous stratigraphic section (Fig. 12) recognized by Lee (1912a) included (in ascending order) the Dakota Sandstone, Mancos Shale (with several informal units and the Tres Hermanos Sandstone Member of Herrick in the lower part), Mesaverde Formation (with Herrick's Punta de la Mesa Sandstone Member at its base), Lewis Shale, and "Laramie" Formation (with a major sandstone, soon to be formally named Pictured Cliffs, at its base). Whether the "Laramie" of the San Juan Basin was actually the same formation and age as the Laramie in its type area in Colorado was regarded as doubtful, a conclusion that would soon be verified by other USGS geologists (see below, p. 23). Lee found the youngest Cretaceous units everywhere terminated by an unconformity above which various early Cenozoic strata rested, such as the Animas Formation in southwestern Colorado, the Puerco Formation farther south, and the Galisteo Formation and equivalent units in the Hagan Basin and Cerrillos areas.

This paper represents a major advance in understanding of the Cretaceous–early Cenozoic stratigraphy of New Mexico. With the regional perspective that his data allowed, Lee was able to trace thickness variations and facies changes within formations, and with abundant paleontological data, to recognize that formations such as the Mancos and Mesaverde transgressed time boundaries across northwestern New Mexico (see Fig. 13 for the modern interpretation of Late Cretaceous stratigraphy). The post-Cretaceous unconformity identified in the Raton Basin seemed clearly to be present in the San Juan Basin as well, and Lee (1912a, p. 613) concluded that from "a diastrophic viewpoint, this unconformity is the logical place of separation between the Cretaceous and Tertiary in the Rocky Mountain region." Lee correctly viewed the Cretaceous sequences in the Raton and San Juan Basins as broadly similar and once continuous around the area now occupied by the southern Rocky Mountains (Sangre de Cristo Range). He stated (p. 614) that "there seems to have been no orogenic disturbance in the mountain region before the end of the Cretaceous…" and at "the close of the Cretaceous the first great upheaval of mountains occurred and erosion naturally began on all sides of them…" This erosion was said to have removed thousands of feet of Cretaceous rock and was reflected in the regional post-Cretaceous unconformity. This proved to be incorrect, but in a very general way, without using the term, Lee was describing a regional manifestation of the Laramide orogeny.

About the same time Lee (1912b, 1913a) contributed short but detailed papers on the Tijeras and Cerrillos coal fields east of the Sandia Mountains. He accurately mapped the Mancos and Mesaverde outcrops within the Tijeras graben and the [Gutierrez] fault along its southeastern margin that juxtaposes Cretaceous strata against "redbeds" [Lower Permian strata].

Lee's 1913 report on the Cerrillos (including the Madrid) coal field expanded upon earlier descriptions of the exposed strata that Douglas Johnson (1902–1903) had incorporated into his large study of the Cerrillos Hills area. Johnson's study, his doctoral dissertation, was one of the finest regional geologic studies done in late territorial New Mexico, encompassing the stratigraphy, paleontology, igneous geology, geomorphology, and economic geology of this area. He had divided the Upper Cretaceous strata into Dakota, Fort Benton, and Fort Pierre, and named the thick, overlying coal-bearing sandstones the "Madrid Coal Group," which in turn was overlain by the Galisteo, which he believed to be probably of latest Cretaceous age. Johnson had gone as far as to study individual coal beds and to do a quantitative analysis of the estimated transmission of heat from nearby dikes, relating that to the degree to which the coals were altered. Lee (1913a) revised Johnson's Late Cretaceous nomenclature to fit it into the developing regional Dakota–Mancos–Mesaverde model, considered individual coal beds in detail using drill hole and structural information, and discussed the relationship between local igneous intrusive bodies and the occurrence of anthracite, an economically valuable type of metamorphosed coal that is otherwise absent in New Mexico.

Lee depended greatly, especially in his studies of the Raton Basin, on the paleobotanical data provided by Knowlton for age determination of the coal-bearing strata. Knowlton (1913) summarized preliminary observations on the floras of the strata below (Vermejo Formation) and above (Raton Formation) Lee's regional unconformity. He maintained that these floras had almost no species in common, that the Vermejo flora was most similar to that of the Mesaverde Formation (thus, pre-Laramie), and that the Raton flora was correlated with that of the Denver Formation in the Denver Basin of Colorado, which was considered to be of Eocene age. Based on Knowlton's study of the fossil plants, Lee's unconformity appeared to be quite significant, representing many millions of years. Even at that time, however, there were problems with Knowlton's interpretations, as dinosaur bones are also found in the Denver Formation. Either its "Eocene" floras were older than realized or, as Knowlton and others, including Lee (1913b) argued, dinosaurs continued on into the early Cenozoic from the Cretaceous.

By the time New Mexico became a state, then, knowledge of the details of Cretaceous stratigraphy and the occurrence of coal in several parts of the Cretaceous sequence had advanced enormously beyond what was known only 10 years before. The work of Lee and other USGS geologists on the Cretaceous continued unabated into the 1920s and 1930s. It is beyond the scope of this paper to survey this work in detail, but a few comments are appropriate in order to complete discussion of some of the strands of research that had been initiated before 1912. Lee (1915) attempted an ambitious general correlation of Cretaceous strata throughout the Rocky Mountain region, from New Mexico to Wyoming. In doing so he laid out quite clearly (see especially his fig. 12) the transgressive-regressive nature of many units in the San Juan Basin, laying the conceptual groundwork for the classic study of Sears et al. (1941) and the modern interpretation of San Juan Basin Cretaceous stratigraphy (e.g., Fig. 13). The complete results of Lee and Knowlton's studies of the Raton Basin were published in a 450-page monograph, consisting of Lee's (1917b) study of the geology and stratigraphy and Knowlton's (1917) study of the fossil plants. Lee's work, augmented by several other publications in the early 1920s, formed the primary source of information on the stratigraphy and general geology of the Raton area for several decades.

Neither Knowlton's plant taxonomy nor his age determinations for the Vermejo and Raton floras proved to be as enduring. The paleobotanist Roland Brown, studying Cretaceous and early Cenozoic floras of the Western Interior, concluded (Brown 1943) that the lower few hundred feet of the Raton Formation, sparse in fossil plants and lacking in coal, was of Cretaceous age, that the supposedly large unconformity between the Vermejo and Raton Formations represented only a short interval of time, and that the upper part of the Raton Formation, rich in coal and plants, is of Paleocene age. Further, he ascertained that only the lowest part of the Vermejo contains pre-Laramie plants, with the flora of most of the formation being correlative with the latest Cretaceous Laramie flora farther north.

And finally, while Lee and Knowlton were studying the Raton Basin, a USGS field party led by C. M. Bauer in 1915 examined the coal-bearing "Laramie" beds along the west side of the San Juan Basin, mapped the area in detail, refined the stratigraphic nomenclature, and collected many plant and vertebrate fossils (studied by Knowlton and Gilmore, respectively). Bauer (1916) introduced the name Pictured Cliffs Sandstone, as well as Fruitland and Kirtland Formations (for the coal-bearing sequence referred to earlier as "Laramie"), and formalized the name Ojo Alamo Sandstone for the sandstone overlying the coal-bearing units. Subsequent papers by Bauer and Reeside (1921) and especially the synthetic work of Reeside (1924) provided a modern foundation for the stratigraphy of the San Juan Basin.

Although most Cretaceous exposures in New Mexico are in the San Juan and Raton Basins and neighboring areas, other Cretaceous sequences were known by 1912, and the mostly sandy strata immediately overlying coal-bearing sandstones of the Mesaverde Group were proving difficult to date. In the Cerrillos–Madrid area, the sequence above Johnson's "Madrid Coal Group" (= Mesaverde Group) had long been known as the Galisteo Formation since Hayden had first named the "Galisteo sands" in the 1860s. The Galisteo here is 1,000 or more feet thick and contains much petrified wood but at the time no animal fossils were known. Although Hayden had considered it of Tertiary age, Lee, Johnson, and Lindgren et al. (1910, p. 34) leaned toward a Cretaceous age, and they considered it possibly correlative with a clastic red-bed sequence near Elephant Butte (now the McRae Formation) from which dinosaur bones were known. However, by 1912 Lee (1912a), although admitting that (p. 610) "Nothing has been found in the Galisteo to establish its geologic age," thought that the Galisteo was more likely of early Tertiary age based on stratigraphic position and lithologic similarities to other early Tertiary formations to the north. Several decades later Eocene mammal fossils were discovered in the Galisteo, providing definite evidence of its age.

In south-central New Mexico around Engle and Elephant Butte, sandstones and shales of Late Cretaceous age were known to be overlain by sandstones containing coal (broadly, the Mesaverde Group), and the upper part of this Cretaceous sequence, consisting of red sandstones and shales, had yielded very Late Cretaceous dinosaur bones (the lower part of the present McRae Formation). Late Cretaceous strata also were known to be present in the Silver City area, but these had not been studied in detail.

Cenozoic

Many 19th and early 20th century geologists reported Cenozoic strata across the territory, and large areas of young unconsolidated sediments were among the most obvious geologic features observed in local and regional studies. However, few detailed studies of older Cenozoic units or younger (Neogene) sediments had been attempted by 1912. Terms like "lake bed" and "ancient river" sediments, and "valley-fill deposits" were widely used, but only a handful of lithostratigraphic names had been published. Much of the information available on Cenozoic stratigraphy was assembled in conjunction with collection and study of the vertebrate fossils contained in some deposits, which provided ages for several important New Mexico sedimentary units.

In the 1870s E. D. Cope had applied the name "Puerco marls" (or group) to strata above the "Laramie" in the San Juan Basin, and a little later the "Puerco" began to yield important new "basal Eocene" (= Paleocene) mammal faunas (see paleontology section). By 1900 the name Torrejon Formation was established (e.g., Matthew 1899) for the upper part of Cope's "Puerco" that yielded slightly younger faunas than the restricted underlying Puerco Formation. Gardner (1910d), as an outgrowth of his studies of coal-bearing Cretaceous strata in the San Juan Basin, produced a detailed study of the overlying Paleocene strata, published in the *Journal of Geology* rather than as a USGS publication presumably because the Paleocene strata lack coal and was outside the scope of the survey's coal program. Gardner reviewed the considerable 19th century history of study of the Puerco and Torrejon mammal faunas and the equivalent formation names, presented his stratigraphic observations but little new information about the faunas, and brought the two formations together within a Nacimiento Group. He noted (p. 736) that "lithologically the Torrejon is not sufficiently distinct from the Puerco to permit its being readily mapped in the field, the separation being made on fossil evidence." Gardner was correct, but Puerco and Torrejon continued being used as formation names for several decades before the U.S. Code of Stratigraphic Nomenclature mandated that lithostratigraphic units like formations should be based only on lithologic, not paleontologic features. Accordingly Simpson (1959) eventually recommended use of the term Nacimiento Formation for the strata bearing Puercan and Torrejonian mammal faunas.

Gardner (1910d) also mentioned that at Ojo Alamo he had collected dinosaur bones from beds similar to the Puerco but unconformably above the "Laramie," the implication being that the bones were post-Cretaceous. That same year Brown (1910) had coined the name "Ojo Alamo beds" for dinosaur-bearing shales below the unconformity with the Puerco. The age, fauna, and stratigraphic relationships of the Ojo Alamo Formation would be discussed in many later papers.

Before leaving these early studies of Paleocene strata in the San Juan Basin, one more paper should be mentioned, because it was stimulated by and a reaction to Gardner's study of the "Nacimiento Group." Sinclair and Granger, of the American Museum of Natural History in New York, in 1912 initiated field studies of the Puerco and Torrejon Formations, noting that (Sinclair and Granger 1914, p. 298) Gardner's observations only covered a portion of the outcrop area "of the two formations, and were made without the aid of sufficient paleontologic data." Their fossil collections of 1912 and 1913 exceeded all previous collections (see paleontology section), but their 1914 paper was primarily stratigraphic and reflected the first detailed field survey of nearly all San Juan Basin outcrops of Paleocene strata.

Sinclair and Granger first elucidated the stratigraphy of the Ojo Alamo beds, noting a prominent conglomeratic sandstone with fossil logs and a dinosaur vertebra, overlain unconformably by the Puerco Formation and underlain by Brown's (1910) "Ojo Alamo beds." Based on their detailed field observations, they (p. 304) stated that not one fragment "of dinosaur bone did we find above the level of the unconformity at the top of the conglomeratic sandstone with fossil logs," and concluded "we feel reasonably certain that dinosaurs will not be found to occur in the Puerco." That conclusion has stood the test of time, although the possibility of Paleocene dinosaurs was seriously discussed into the 1920s, and has resurfaced occasionally through the rest of the 20th and into the 21st century.

Sinclair and Granger (1914) also described the stratigraphy and areal distribution of San Juan Basin Paleocene strata with much greater detail than had Gardner, documented more precisely the stratigraphic distribution of the Puercan and Torrejonian faunal horizons, reported the first plant assemblages, interpreted the fluvial sedimentology of the sequence, and even speculated on the taphonomy of the mammal remains. Although recognizing that there is no marked lithologic difference and no unconformity between the Puerco and Torrejon "formations," they saw no need for Gardner's term Nacimiento Group, as at that time distinctive fossil faunas were considered a legitimate basis upon which to recognize separate formations. For the benefit of future workers, they included many photographs of important Paleocene exposures. Completed outside the aegis of the USGS, Sinclair and Granger's (1914) paper was an important contribution to the stratigraphy of the San Juan Basin.

A younger unit overlying the "Nacimiento Group" had long been known in the San Juan Basin. Cope had described many Eocene vertebrates from it, and it was called the Wasatch Formation in the literature of a hundred years ago. However, the type Wasatch is in Wyoming, and the name as applied to New Mexico strata in the 20th century was more based on faunal similarities with Wasatchian mammals in the northern Rockies than on a presumption that it was actually the same formation. Much later (Simpson 1948) the name San Jose Formation was applied to this early Eocene unit on the eastern side of the San Juan Basin. As noted above, the Galisteo Formation south of Santa Fe was beginning to be considered of early Tertiary rather than Late Cretaceous age around the time of statehood, but no equivalent early Tertiary strata had been identified in southern New Mexico.

By 1912 Neogene strata had been reported throughout New Mexico, but little detailed stratigraphic study of these locally thick sequences had been attempted, and except in a few cases where vertebrate fossils had been identified, precise ages were lacking. The earliest named of these strata, the "Santa Fe marls" of Hayden in the 1860s, had produced mammals described by Cope in the 1870s, and its age was considered to be Miocene to possibly Pliocene. Lindgren et al. (1910, p. 33) noted that "a lake of large extent appears to have existed in the upper Rio Grande valley," in which the Santa Fe sediments had been deposited. At this time most vertebrate fossil-bearing deposits throughout the Cenozoic in the western U.S. were thought to have been deposited in lacustrine environments (e.g., Matthew 1899). To the east, across the Great Plains region east of the central New Mexico mountain chains, a mantle of sand and gravel at least partly correlative with the "Santa Fe marls" was known to be distributed widely. Similar deposits had been described in western Nebraska by Darton (1899) and named the Ogallala Formation, but it apparently took nearly three decades for the term Ogallala to be formally applied to these New Mexico strata (Darton, 1928, p. 58).

Thick deposits (1,000–1,500 feet) of conglomerate and sandstone filling the valleys between the mountains in southeast Arizona and southwest New Mexico had been named the Gila Conglomerate by Gilbert in the mid-1870s. Based on stratigraphic position and relationships to some interbedded young basalt flows, the Gila was believed to be of early Quaternary age. Much additional later work has shown that the Gila encompasses a much longer period of deposition, from the Oligocene to early Pleistocene in some areas (e.g., Mack 2004). Similarly, the older portions of sand and gravel deposits as much as 2,000 feet thick within the valley of the central and southern Rio Grande and its tributaries, observed covering the base of some ranges to a height of 1,500 feet above the river, were called the "Palomas gravels." These were considered to be of early Pleistocene age, and possibly correlative with the Gila deposits to the west (Lindgren et al. 1910, p. 237). Recognition of these coarse sediment deposits, derived from erosion of the surrounding highlands, reflects very general observations of what was later to prove to be a much more complex, thicker, and longer pattern of sediment deposition in subsiding basins of the Basin and Range and Rio Grande rift regions over the past 25 to 30 million years.

Paleontology

Introduction

Fossils were reported and identified from strata in many parts of New Mexico by the first explorers and geologists to enter the territory during and immediately following the Mexican–American war. Because they were the primary method of determining the ages of sedimentary rocks, paleontologic collections were assembled and studied throughout the 19th and early 20th centuries as the stratigraphy of New Mexico was being worked out (see previous section). By 1912 invertebrate and/or vertebrate faunas had been at least cursorily studied from strata representing each of the geologic periods from the Cambrian through Cretaceous. In the Cenozoic, important vertebrate faunas had been described from Paleocene, Eocene, and Miocene strata, but none were then known from the Oligocene or Pliocene, and only a few mammal bones had been reported from the territory's widespread exposures of Pleistocene sediments (Kues 1993).

Invertebrates

For Paleozoic and Mesozoic marine strata, sufficient information (identified genera and species) was available to allow determination of the ages of some formations, but few descriptive studies documenting and illustrating these faunas had been published by the beginning of the 20th century. Most of these dealt with either Pennsylvanian or Cretaceous fossils—not surprising in view of the fact that strata of these ages are widely exposed in New Mexico and yield the most diverse assemblages of fossils in

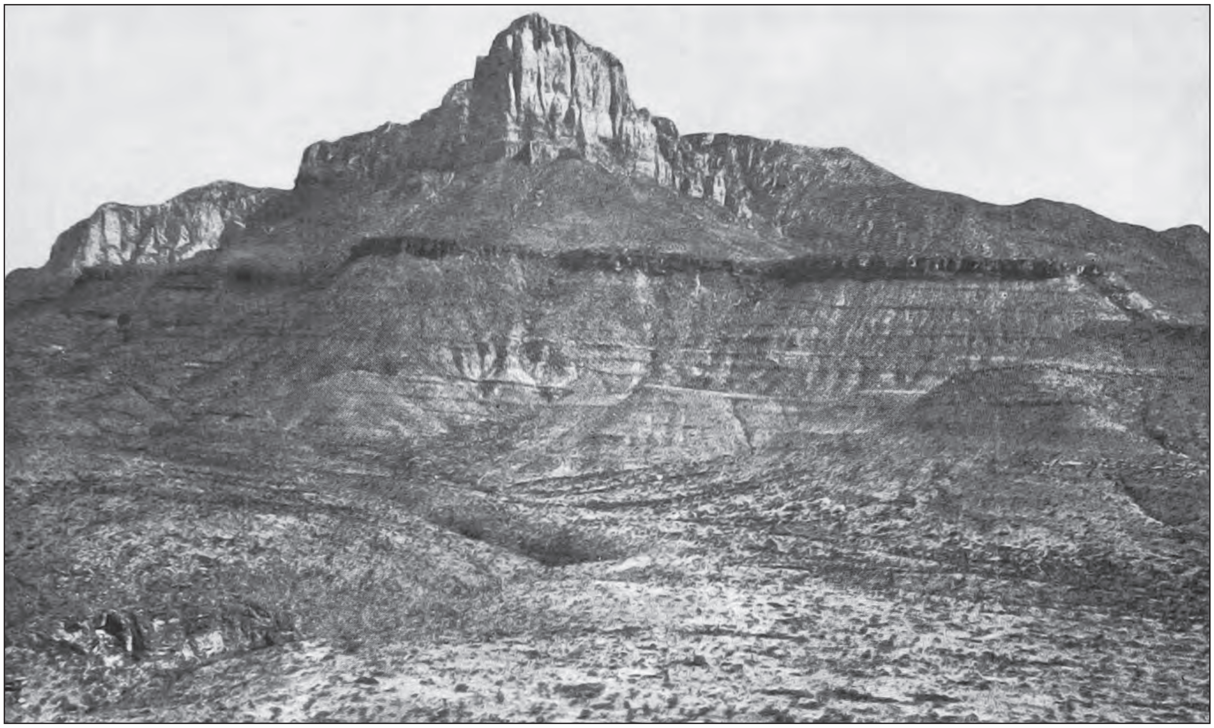

FIGURE 14—South end of the Guadalupe Mountains, source of Girty's (1908) prolific Permian faunas (Richardson 1904, pl. 4A).

the state. Scattered descriptions of fossils, with some new Pennsylvanian and Cretaceous taxa proposed, appear in the reports of early explorer–geologists (e.g., Hall 1856; Conrad 1857; Marcou 1858; Newberry 1861; Meek 1876). White (1881) described a small portion of a Pennsylvanian fauna near Taos (which had been collected by Cope on the Wheeler survey) and included New Mexico fossils in several other papers, and Stanton (1893) included much information on New Mexico Late Cretaceous invertebrates in his monograph on Colorado-age (early Late Cretaceous) faunas of the Western Interior. A flurry of papers on the purported Jurassic (but actually late Early Cretaceous) faunas in the Tucumcari area in the 1890s, and Hill and Vaughn's (1898) monograph on the oysters later known as *Texigryphaea* (the most abundant fossils at the Tucumcari localities) had made these arguably the most intensively studied marine fossil assemblages in the territory.

Excluding Pennsylvanian and Cretaceous fossils only the diverse Early Mississippian faunas near Lake Valley had received modest attention. Frank Springer (1884), a noted territorial lawyer and paleontologist (see Caffey 2006), discussed many taxa, though without illustrating them, and a few of the Lake Valley Limestone's famous crinoids were included in Wachsmuth and Springer's (1897) monograph.

Studies of the territory's marine fossils continued in the years leading up to statehood. Herrick and Johnson (1900) described many Late Cretaceous invertebrates from central New Mexico (although their illustrations were taken from Stanton, 1893), and Herrick (in several papers but especially 1900b) illustrated many Pennsylvanian taxa from the Albuquerque area and the Sacramento Mountains as part of his geologic reconnaissances of the territory. His student Douglas Johnson produced a monograph on the Late Cretaceous faunas of the Cerrillos Hills area (Johnson 1902–1903) that was only a part of his overall study of the geology of the area, but at the time it was the most comprehensive treatment of a large and diverse invertebrate fauna that had been done in New Mexico.

Several major monographs on fossil marine invertebrate assemblages in and close to New Mexico were published in the years just before statehood. The first was George Girty's great study of the Permian faunas of the Guadalupe Mountains (see historical summary by Kues 2006). Girty, the USGS specialist on late Paleozoic fossils, spent 11 days in 1901 collecting from the massive limestones (now Capitan Limestone) at the southern end of the Guadalupe Mountains (Fig. 14), just across the border in Texas—rocks that had yielded sparse Permian fossils in the 1850s. He immediately recognized that these faunas were different from any that had been encountered previously in North America, and in two short papers Girty (1902, 1905) discussed the evidence for their Late Permian age. His 651-page monograph (Girty 1908) included descriptions of 326 species, more than half of them new, mainly brachiopods, bryozoans, bivalves, gastropods, and sponges. He was well aware that he had only scratched the surface of these remarkably rich fossil deposits, and that many more species awaited collection and description. Studies over subsequent decades, including large programs of acid-etching silicified fossils from blocks of limestone by the Smithsonian Institution and American Museum of Natural History, and recognition (Lloyd 1929) of the Capitan Limestone and associated formations as parts of a gigantic reef complex, have made the Guadalupe Mountains Permian faunas world famous, and paleontologic studies have continued to the present. The locations where Girty collected are now part of Guadalupe Mountains National Park.

Although Girty's initial Guadalupian collections and monograph were, strictly speaking, from Texas, not New Mexico, he and others soon extended their observations northward into New Mexico (e.g., Girty 1909) and began to study the relationships of these strata and faunas with those of the Permian of southern and central New Mexico. A second important contribution to New Mexico Permian paleontology was Girty's monograph on the invertebrates of the "Manzano Group," done in concert with Lee's stratigraphic studies (Lee and Girty 1909) establishing the Abo, Yeso, and San Andres Formations (see discussion in Stratigraphy section above, p. 17). These faunas were relatively sparse and generally not well preserved, but Girty's studies represent the beginning of our knowledge of the marine paleontology of these widely exposed formations.

The third important lengthy study of New Mexico marine invertebrates just before to statehood came from an entirely different direction—a monograph on Early Cretaceous faunas of the area around Cerro de Cristo Rey (known at the time as Cerro de Muleros), an exposed mid-Cenozoic intrusion along the Rio Grande, opposite El Paso, Texas, and straddling the New Mexico–Chihuahua (Mexico) border. This was written by a German geologist, Emil Böse (1910), who worked for the Instituto de Geologia de Mexico from 1898 to 1915 before moving to the Texas Bureau of Economic Geology. Böse carefully described the stratigraphy of the strata surrounding the instrusion and studied the paleontology of each formation in great detail, correlating the faunas to those of Albian (late Early Cretaceous) units of Texas. His work on the Cretaceous of Cerro de Cristo Rey has stood the test of time quite well and remains as a foundation of knowledge of Early Cretaceous paleontology in New Mexico, accurate and useful to the present.

A few other contributions to the invertebrate paleontology of the state during these years deserve mention. Hyatt (1903), in a posthumously published monograph on Cretaceous ammonites, established the genus *Coilopoceras* and three of its species for a large and characteristic Turonian-age ammonite found in New Mexico. Shimer and Blodgett (1908) surveyed the Late Cretaceous faunas of the Mt. Taylor area, and Kindle (1909) described several characteristic Devonian invertebrates from southern New Mexico, thereby verifying the presence of Devonian strata in the territory.

By 1912 then, invertebrate taxa, including a moderate number of new genera and species, had been identified from many Paleozoic and Cretaceous strata and localities, but only a few of these assemblages had been studied in detail. The Permian fossils from the Guadalupe Mountains comprised the most diverse, unique, and significant marine faunas yet described from the New Mexico region, and most of these were collected from localities just across the border in Texas.

Vertebrates

At the turn of the 20th century New Mexico's vertebrate fossil record was more widely known than its invertebrate faunas, largely because of the work of the renowned vertebrate paleontologist Edward Drinker Cope in the territory. Cope had explored north-central New Mexico while a member of the Wheeler Survey in 1874, and had discovered rich Eocene ("Wasatchian") and important Triassic and Miocene (from the "Santa Fe marls") vertebrate deposits, which he described in many papers (see especially Cope 1877). A little later he hired a professional fossil collector, David Baldwin, to collect from the strata of the San Juan Basin, and by the early 1880s Baldwin had discovered the first dinosaur fossils as well as the prolific "Puerco" (Nacimiento Formation) Paleocene mammal faunas, which Cope described in a long series of papers through the 1880s (see especially Cope 1888, in which he recorded 106 species of Paleocene vertebrates). Previously, Baldwin, working first for Cope's rival, Othniel Marsh, of Yale University, had sent Marsh (and later Cope) collections of Permian vertebrates from north-central New Mexico. Neither paleontologist did much with them, but brief papers at least placed a few of the vertebrates on record. Finally, scattered marine Pennsylvanian fish teeth and Cretaceous shark and other fish teeth as well as very fragmentary plesiosaur and mosasaur remains were also known from New Mexico by 1900.

Of these discoveries, the Paleocene fossils attracted the most interest, as they represented by far the best record of primitive mammals immediately following the extinction of the dinosaurs of any region in the world, and included many previously unknown mammal groups. The American Museum of Natural History in New York sent expeditions to the San Juan Basin in 1892 and 1896 to follow up on Baldwin's and Cope's discoveries, and in 1895 the museum bought Cope's Paleocene collections, immediately becoming the foremost institution in the study of these early mammals. Study of and publication on these collections continued through 1900. By this time the Paleocene faunas (although the term Paleocene had not come into wide usage) of the San Juan Basin were acknowledged as being of fundamental importance in understanding the early evolution of mammals, and were undoubtedly New Mexico's main claim to paleontological fame.

Further work on the Paleocene of New Mexico commenced in 1907 with Gardner's field studies of the Nacimiento "Group" (Gardner 1910d; see Stratigraphy section, p. 23), followed by additional American Museum expeditions led by Walter Granger in 1912, 1913, and 1916. These expeditions, in addition to collecting hundreds of new specimens of Paleocene mammals, also for the first time provided exact stratigraphic contexts for the Nacimiento faunas, and ultimately led to W. D. Matthew's great monograph on these vertebrates, published posthumously in 1937. Additions to our knowledge of New Mexico's Paleocene fauna have continued to the present.

Collection and study of San Juan Basin Cretaceous vertebrate fossils began later and proceeded more slowly than that of the Nacimiento mammals. The first significant collections were made by another American Museum paleontologist, Barnum Brown, during a short reconnaissance trip in 1904. This excursion produced several new species of turtles, described by Hay (1908), and the type specimen of the first well-preserved dinosaur described from New Mexico, the skull of a new genus of hadrosaur, *Kritosaurus navahovius* (Brown 1910). These fossils were collected from what were then called the "Laramie beds," or as Brown termed them, the "Ojo Alamo beds," part of the Kirtland Formation of modern usage. A few years later, in 1908 and 1909, Gardner collected some additional material, including two more new turtles described by Hay (1910). Likewise, during his 1912 field season in the San Juan Basin, Granger made a small collection of Cretaceous dinosaurs while spending most of his time on Nacimiento exposures.

Meanwhile, in southern New Mexico, Lee (1906, 1907a) had reported a partial skeleton of *Triceratops*, a Late Cretaceous horned dinosaur, from what later became known as the McRae Formation near Elephant Butte. Little was collected before Elephant Butte reservoir covered the area, but the ceratopsian Lee discovered was later determined to be indeterminate or perhaps another genus such as *Torosaurus*, and the McRae now is known to contain a dinosaur fauna of modest diversity and of very late Cretaceous age (e.g., Lucas et al. 1998).

By 1912, then, nothing resembling a "dinosaur rush" was happening in the new state, but what had been collected had generated interest. Three years later the USGS sent a field party led by Clyde Max Bauer to the San Juan Basin, mainly to figure out the stratigraphy of the "Laramie" beds between the youngest marine strata and the base of the Nacimiento Formation, but also to collect fossils. That party secured the largest collections of vertebrates yet extracted from the Upper Cretaceous beds (as well as many plants and nonmarine molluscs); the vertebrates (dinosaurs and turtles) were described by Charles Gilmore of the Smithsonian Institution in a series of papers beginning in 1916. Study of the vertebrate faunas of the Fruitland and Kirtland Formations has advanced steadily, if incrementally, since then, with almost continuous collecting from the 1970s to the present. Many new dinosaurs, together with smaller vertebrates such as amphibians, lizards, crocodylians, and mammals, have been added to what has become one of the most important Late Cretaceous vertebrate faunas in North America.

Cope's 1874 to 1877 papers on the "Wasatch" vertebrates of what is now known as the San Jose Formation in the San Juan Basin had documented a rich and important early Eocene fauna with many new mammals as well as reptiles and a large bird, a total of about 70 species. However, Cope's work was not significantly augmented by subsequent collection or studies, and little new information had been added by 1912. His competitor, Othniel Marsh, described several new mammals in the 1890s, but these were based on very limited material, and all turned out to be synonyms of Cope's species. Hay (e.g., 1908) added some new turtles to the San Jose fauna. The attention of the American Museum had shifted largely to the richly fossiliferous Eocene beds in Wyoming, but Granger made additional collections from the Eocene during his field work in the San Juan Basin in 1912 and 1913. These were used by Matthew and Granger in their revision of North American Eocene mammals in several papers from 1915 to 1918, which added a few new mammal genera to the San Jose fauna. Study of New Mexico's Eocene vertebrates then largely lapsed until the 1940s.

Cope's initial studies in the 1870s of Miocene vertebrates from the badlands of the Rio Grande valley north of Santa Fe had yielded about 27 species, many of them new. They included tortoises, a vulture, and varied mammals (species of rabbits, rodents, horses, rhinos, camels, pronghorns, oreodonts, proboscideans, canids, and skunks). This fauna was diverse and should have prompted further collecting efforts, but in 1912 Cope's reports of more than 35 years before were all that was known of the paleontology of the "Santa Fe marls." It was not until the mid-1920s that large-scale collecting by the American Museum of Natural History commenced, and this persisted nearly annually for the next 40 years, producing most of what is known of New Mexico Miocene vertebrates. These faunas now include more than 125 species and constitute one of North America's best records of vertebrate evolution from about 20 to 5 million years ago.

Cope's discovery of the first Triassic vertebrates in the American West was made in the red beds now called the Chinle Group in the Gallinas River valley northeast of Cuba. From this material he described the first known American aetosaur, *Typothorax*, and sent some freshwater clams to F. B. Meek, who described three species of unionid bivalves, the oldest then known in North America. Later, in the 1880s David Baldwin, while employed by Cope, collected additional vertebrate remains from Triassic exposures extending eastward to Ghost Ranch. These included the skull of a new phytosaur and the fragmentary remains of an early theropod dinosaur, *Coelophysis*, both described by Cope in the 1880s. No additional publications on New Mexico Triassic vertebrates had appeared by the time statehood was attained.

The large area of Triassic outcrops in northern New Mexico, and the few but intriguing fossils Cope had reported did stimulate additional prospecting and collecting. A field party led by Samuel Williston in 1911 (see below), while primarily searching for Permian vertebrates, collected some Triassic material in the Ghost Ranch area, and in 1912 and 1914 E. C. Case (University of Michigan) and M. G. Mehl (University of Wisconsin) collected more Triassic vertebrates from new areas—near San Jon and in Bull Canyon in east-central New Mexico, and near Fort Wingate in west-central New Mexico (see Long and Murry 1995, for detailed history of Triassic collecting in New Mexico). Knowledge of the new state's record of Triassic vertebrates increased gradually through subsequent decades, with parties from several institutions (University of California, Harvard, American Museum of Natural History, University of Michigan) collecting in the 1920s and 1930s. The discovery of the amazing concentration of complete *Coelophysis* skeletons at Ghost Ranch by an American Museum party in 1947 elevated New Mexico's Triassic faunas to international prominence, and the pace of new discoveries has only increased to the present.

By 1912 New Mexico was also becoming known for much older vertebrate fossils, from Late Pennsylvanian and Early Permian red beds near Arroyo del Agua (east of Cuba) and El Cobre Canyon (near Abiquiu). These fossils, primarily of amphibians and early reptiles, were initially collected by David Baldwin in 1877 to 1881 and sent to Marsh at Yale, with some later collections going to Cope (see papers in Lucas et al. 2005 for detailed histories of collecting from these areas). Marsh spent little time on these collections but wrote one short paper (Marsh 1878) describing the first incomplete remains of several characteristic genera (*Spenacodon*, *Ophiacodon*, *Diadectes*) of these faunas. Cope also was not impressed with the remains he received, having spent several years prospecting and studying richly fossiliferous Lower Permian deposits in Texas. He described a couple of new vertebrate species from New Mexico in two papers in the 1880s.

The true importance of Baldwin's discovery would not be recognized until more than 30 years after he had sent his first shipment of these fossils to Marsh. Much of this material remained at Yale in unopened boxes until the University of Chicago paleontologist Samuel Williston went through it and had it prepared around 1908–1909. His studies of this material put New Mexico "on the map" as a source of important Early Permian vertebrates. Most important of these fossils was a skeleton of *Limnoscelis*, then considered to be the oldest and most primitive known reptile. As such, it appeared widely in textbooks on vertebrate anatomy, evolution, and paleontology for more than a half century, although now is interpreted as an advanced amphibian.

Williston (1911) also wrote a book, *American Permian Reptiles*, in which New Mexico taxa figured prominently, and that same year he organized an expedition to relocate and recollect from the bone beds at Arroyo del Agua and El Cobre Canyon that Baldwin had discovered. These collections yielded a variety of new amphibians, reptiles, and synapsids ("mammal-like reptiles") that were described in a steady stream of publications by Williston, Case, and others through 1918. This work established New Mexico as one of North America's most important sources of information about Late Pennsylvanian–Early Permian life, a critical time in vertebrate evolution when reptiles were first establishing dominance of terrestrial environments. In subsequent decades much additional material would be recovered from these and other late Paleozoic red-bed strata by various paleontologists, adding both to the list of new genera and species and to the overall quality of specimens representing them. Study of these faunas continues today (e.g., papers in Lucas et al. 2005).

Strata of other geologic time periods in New Mexico had produced few (Jurassic, Pleistocene) or no (Cambrian–Devonian, Pliocene) vertebrates as New Mexico entered statehood. The Jurassic record was limited to a few fragmentary unidentifiable dinosaur bones reported from northeastern New Mexico (Stanton 1905). The large areas of Pleistocene sediments in New Mexico had yielded only a few remains of mammoths reported by Cope from the base of the Sandia Mountains, a few mastodon bones, and one new species of extinct muskox, described by Gidley (1906). Much more attention would be devoted to Pleistocene vertebrates in the 1920s and 1930s, with the discovery of late Pleistocene Paleo-Indian artifacts (Folsom and Clovis spear points) found in association with the bones of large extinct mammals.

One way of appreciating how much our knowledge of the state's vertebrate fossils has grown over the past century is to compare progress in understanding each period's species diversity. Ten years before New Mexico became a state Hay (1902) recorded a total of 219 well-documented extinct fossil vertebrate species from the territory, 76% of which were from the Paleocene and Eocene Epochs. By comparison, 90 years later Kues (1993) tabulated 697 total fossil vertebrate species. Increased study of vertebrates from other times, particularly the Cretaceous (18% of total) and Miocene (16% of total), as described above, had reduced the Paleocene–Eocene proportion to 42%. Fifteen years after that, nearly 100 years after New Mexico became a state, the total number of extinct vertebrate species had grown to 941 (Kues 2008b). Paleocene–Eocene species amounted to 34% of the total, with complementary increases in knowledge of taxa of other periods, such as the Pennsylvanian–Permian, Triassic, and Pliocene. The more than four-fold increase in the number of known extinct vertebrate species over the past century reflects an increased intensity of collection and study, especially within the past 25 years—the time since the New Mexico Museum of Natural History first opened its doors. Yet it is worth remembering that the initial discoveries of many important vertebrate faunas were made during New Mexico's territorial years, and that these discoveries kept paleontologists returning to New Mexico decade after decade for continued, sometimes fantastically successful prospecting for new vertebrate deposits.

Plants

Plant fossils had been reported in New Mexico rocks since the first geologic observations of the late 1840s. Through the remainder of the 19th century, as the territory was explored and its stratigraphy became better known, plants were observed in beds of various ages, although few detailed studies of them had been done. By 1900 plants had been reported from Pennsylvanian, Permian, Triassic, Cretaceous, and early Cenozoic strata, but only Triassic, Cretaceous, and Paleocene plant fossils had received even a modicum of study. Several new species of Triassic plants, mainly from the area of El Cobre Canyon, near Abiquiu, were described in the 1870s through 1890s by Newberry, Knowlton, and Fontaine. Ironically, identification of the large and colorful logs in northeastern Arizona (now Petrified Forest National Park) as a new species (*Araucarioxylon arizonicum*) by Knowlton (1889) was based partly on a log collected near Fort Wingate, New Mexico.

Cretaceous plant fossils from the Dakota Sandstone of northeastern New Mexico had been studied by Newberry, who described four new species. Most Cretaceous plant species known from the territory, however, were from younger coal-bearing strata in the area of Raton Pass and near Madrid, described by Leo Lesquereux in the 1870s as part of his broader studies of the paleobotany and age of the "Laramie beds" across the Western Interior. Knowledge of Cretaceous plants in the San Juan and Raton Basins increased in the years just before 1912 as Knowlton began studying and identifying species in collections made by Willis Lee in his stratigraphic studies (see Stratigraphy section, p. 21). However, monographic study of the floras of these basins did not appear until several years later (Knowlton 1916, 1917). By 1912, about 40 species of Cretaceous plants were known, with perhaps a dozen more species from strata that eventually turned out to be of Paleocene age.

These early paleobotanical studies involved New Mexico tangentially in one of the longest and most contentious paleontologic controversies of the late 19th century—the geologic age of the so-called "Laramie beds." These coal-bearing and locally profusely fossiliferous strata were exposed widely across the Western Interior, from Montana to New Mexico, and the paleobotanical evidence was believed by geologists such as Lesquereux to indicate an early Cenozoic ("Eocene") age, despite the fact that in some areas dinosaur bones and Cretaceous marine invertebrates were found with the supposedly early Cenozoic plants (see Merrill 1924, pp. 579–593, for extended discussion). What was insufficiently understood at the time was that the term "Laramie" had been rather indiscriminately applied to many formations in the approximate stratigraphic position of the type Laramie (Late Cretaceous) in central Colorado. More detailed stratigraphic and paleontologic studies eventually showed that some of these coal-bearing formations (such as the Fruitland and Kirtland Formations in the San Juan Basin) were definitely of Late Cretaceous age, whereas others, such as the Raton Formation in northeastern New Mexico, were predominately of Paleocene age. This was not entirely clear as New Mexico became a state, and it would not be until the 1930s that the controversy was put to rest.

In 1912 one impressive concentration of Eocene plant remains—logs in a "fossil forest" near Cerrillos—was also well known, although the logs had not been studied by any paleobotanist and their age was not definitely established. These petrified logs were the first fossils ever reported from New Mexico in the published literature (by Gregg 1844), and day trips to see them were occasionally mounted by adventurous individuals from Santa Fe and Albuquerque around the time New Mexico became a state.

By 1912, then, only very preliminary and incomplete information on New Mexico's rich fossil floras was available. A century of subsequent study by paleobotanists has revealed diverse and well-preserved assemblages of Pennsylvanian and Permian plants (see Kues 2008b), and greatly increased knowledge of Late Triassic floras from the Chinle Group, which together with contemporaneous floras from the Petrified Forest in Arizona now represent arguably the best record of Triassic plant life in North America. Likewise, research on Late Cretaceous and Paleocene leaf floras in the state has continued, augmented in recent decades by extensive palynologic studies of microscopic spores and pollen. More modest floras of Eocene, Miocene, and Pliocene age have also been documented since 1912.

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

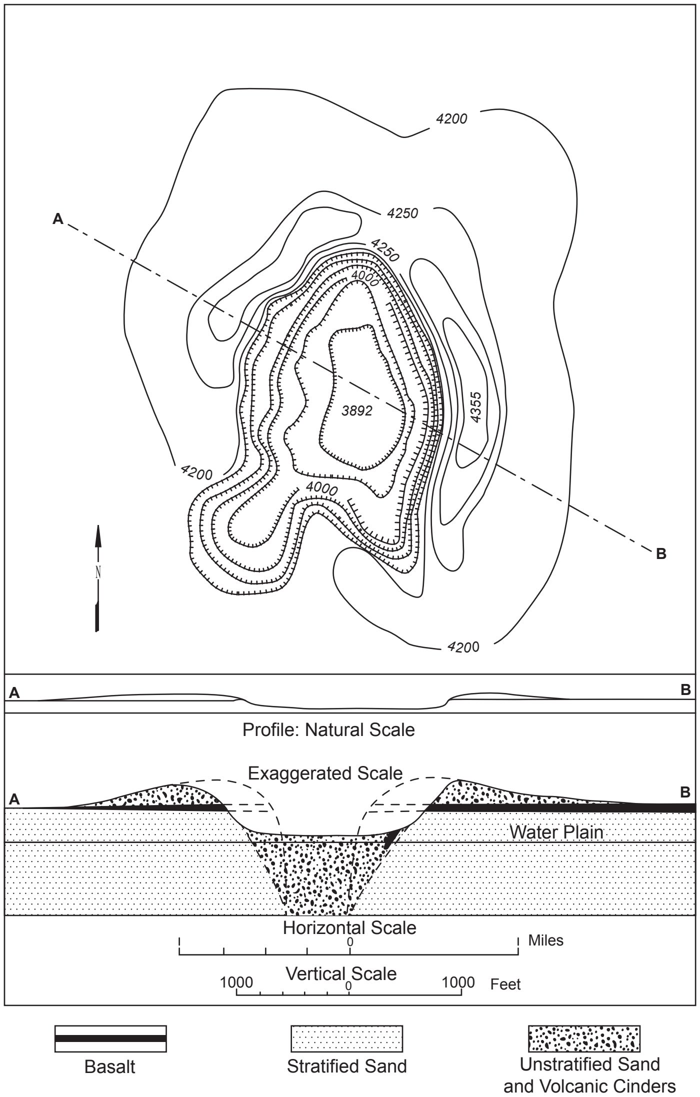

FIGURE 16—One of the "Afton craters" (Kilbourne maar). Redrawn from Lee (1907c, fig. 1).

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. 34), 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. 34). 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.

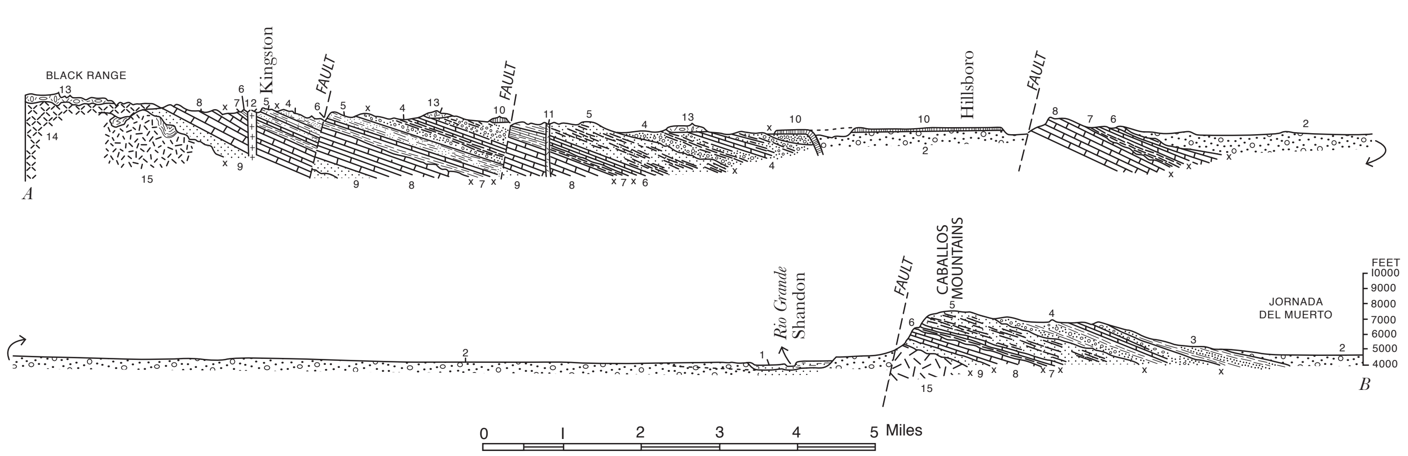

FIGURE 16.—Profile section from Kingston to Jornada del Muerto (along line *A-B*, P1. XII). 1. Lower terrace and flood-plain deposits; 2. Palomas gravel; 3. Cretaceous; 4. Manzano group; 5. Magdalena group; 6. Lake Valley limestone; 7. Percha shale; 8. Mimbres limestone; 9. Shandon quartzite; 10. basalt; 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,

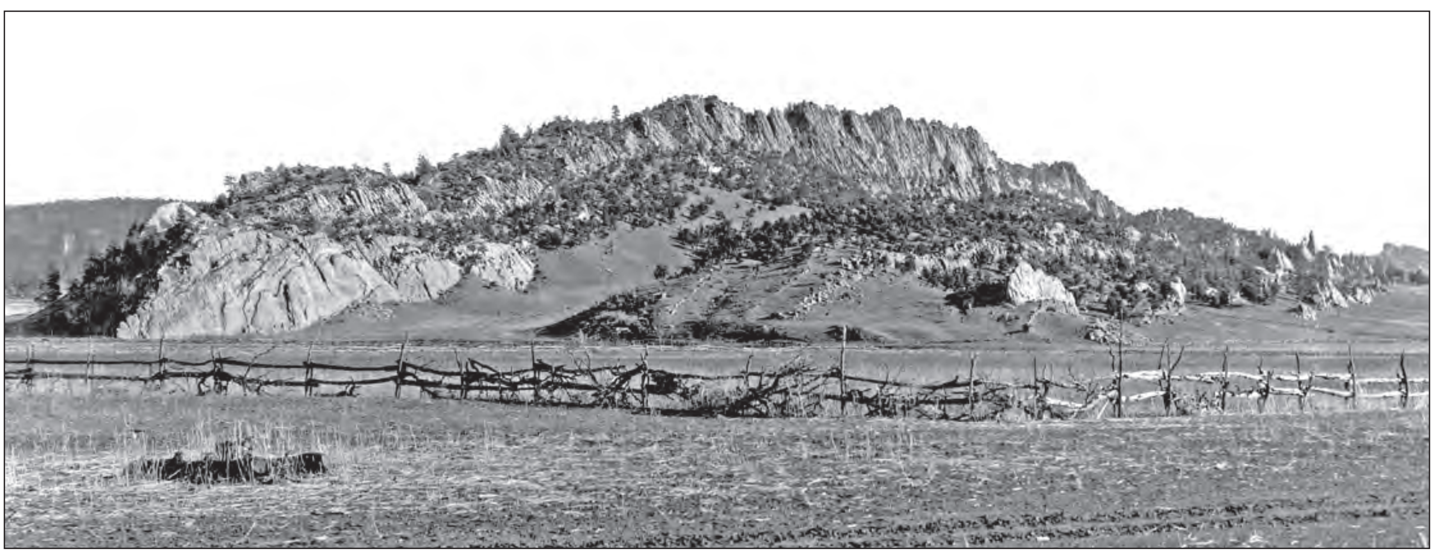

FIGURE 18—Nearly vertical Cretaceous and underlying strata on southwest side of Zuni uplift near Nutria (Darton 1910, pl. 17A), an example of the use of photography in portraying important geologic features in early 20th century USGS reports.

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.

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 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.

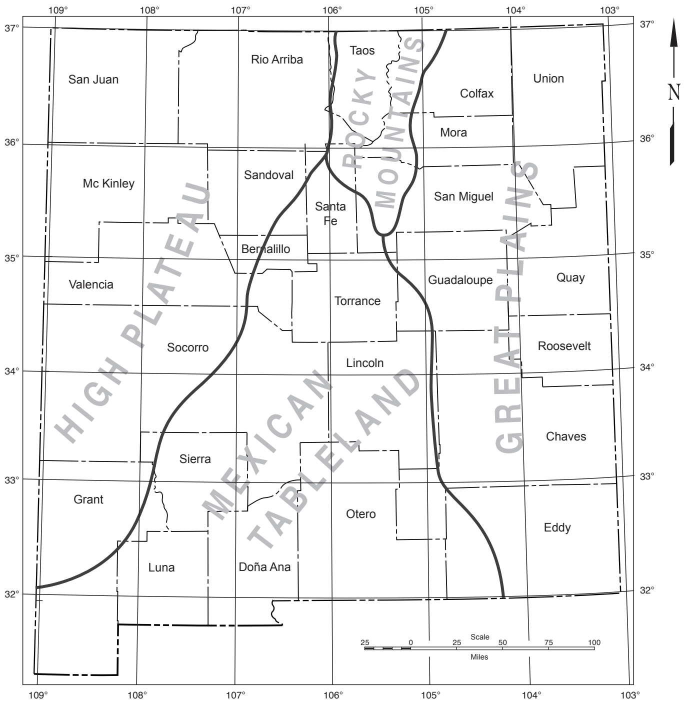

FIGURE 19—New Mexico's physiographic provinces, modified from Keyes (1906).

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

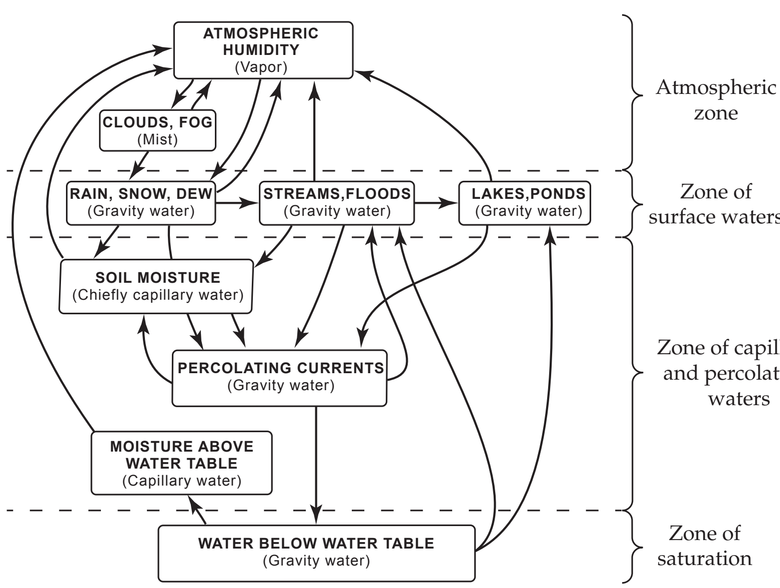

FIGURE 23—Meinzer's concept of the interrelationships between surface and groundwater within the hydrologic cycle (redrawn from Meinzer and Hare 1915, fig. 26).

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

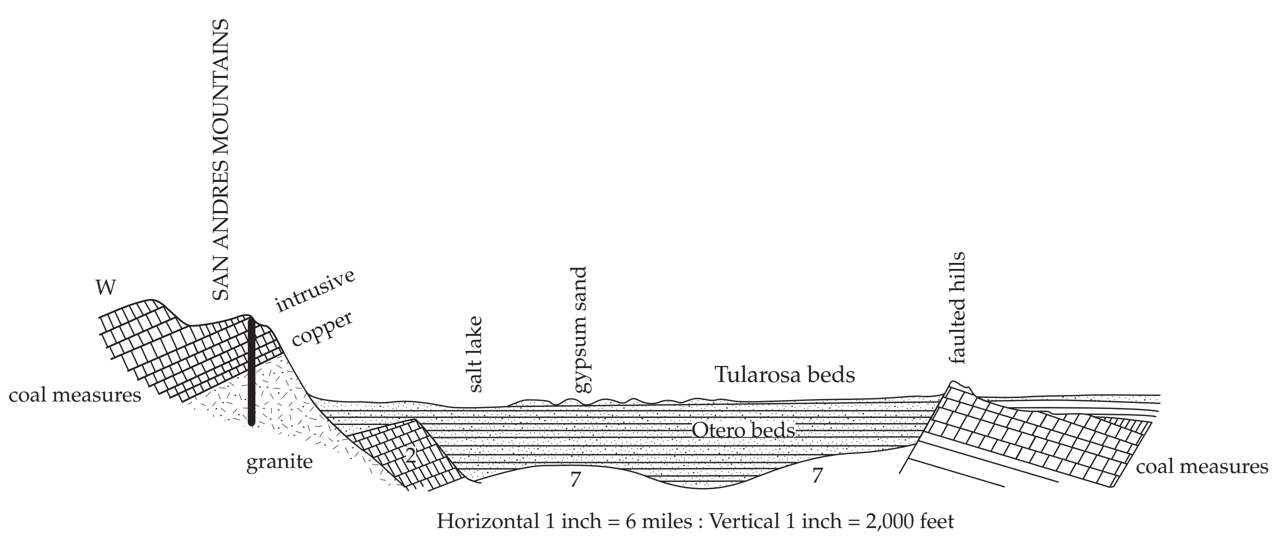

FIGURE 24—Cross section through Pleistocene Lake Otero in the Tularosa Valley (Herrick 1904b, redrawn from Lucas and Hawley 2002).

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.

References

Alden, W. C., 1926, Memorial of Willis Thomas Lee: Geological Society of America, Bulletin, v. 38, pp. 70–93.

Allen, B. D., 2005, Ice age lakes in New Mexico; *in* Lucas, S. G., Morgan, G. S., and Zeigler, K. E. (eds.), New Mexico's ice ages: New Mexico Museum of Natural History and Science, Bulletin 28, pp. 107–114.

Antisell, T., 1856, Report of explorations for railroad routes, San Francisco Bay to Los Angeles, west of the Coast Range, and from the Pimas villages on the Gila to the Rio Grande, near the 32nd parallel of north latitude: geological report; *in* Reports of explorations and surveys to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean, v. 7, pt. 2: U.S. 33rd Congress, 2nd Session, Senate Executive Document 78, 204 pp.

Bandelier, A., 1890, The delight makers: Dodd, Mead & Co., New York, 490 pp.

Barker, F. C., 1898, Irrigation in Mesilla Valley, New Mexico: U.S. Geological Survey, Water-Supply Paper 10, 51 pp.

Bauer, C. M., 1916, Contributions to the geology and paleontology of San Juan County, New Mexico; 1, Stratigraphy of a part of the Chaco River valley: U.S. Geological Survey, Professional Paper 98-P, pp. 271–278.

Bauer, C. M., and Reeside, J. B., Jr., 1921, Coal in the middle and eastern parts of San Juan County, New Mexico: U.S. Geological Survey, Bulletin 716-G, pp. 155–237.

Beck, W. A., and Haase, Y. D., 1969, Historical atlas of New Mexico: University of Oklahoma Press, Norman, not paginated.

Blake, W. P., 1856, Report on the geology of the route, no. 1—General report on the geological collections; *in* Whipple, A. W., Reports of explorations and surveys to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean, v. 3, pt. 4: U.S. 33rd Congress, 2nd Session, Senate Executive Document 76 and House Executive Document 91, pp. 1–91, 106–119.

Boltwood, B. B., 1907, On the ultimate disintegration products of the radioactive elements. Part II. The disintegration products of uranium: American Journal of Science, 4th series, v. 23, pp. 77–88.

Böse, E., 1910, Monografia geológica y paleontológica del Cerro de Muleros cerca de Ciudad Juárez, Estado de Chihuahua, y descripción de la fauna Cretácea de la Encantada, Placer de Guadalupe, Estado de Chihuahua: Instituto Geologico de Mexico, Boletin 25, 193 pp.

Brown, B., 1910, The Cretaceous Ojo Alamo beds of New Mexico with description of the new dinosaur genus *Kritosaurus*: American Museum of Natural History, Bulletin, v. 28, pp. 267–274.

Brown, R. W., 1943, Cretaceous–Tertiary boundary in the Denver Basin, Colorado: Geological Society of America, Bulletin, v. 54, pp. 65–86.

Bryan, K., 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico: regional planning, part 6, upper Rio Grande: National Research Commission, pp. 197–225.

Bryson, B., 2011, At home: Anchor Books, New York, 577 pp.

Burke, W. H., Kenny, G. S., Otto, J. B., and Walker, R. D., 1963, Potassium-argon dates, Socorro and Sierra Counties, New Mexico; *in* Kuellmer, F. J. (ed.), Guidebook of the Socorro region: New Mexico Geological Society, Guidebook 14, p. 224.

Burks, M. R., and Schilling, J. H., 1955, Bibliography of New Mexico geology and mineral technology through 1950: New Mexico Bureau of Mines and Mineral Resources, Bulletin 43, 198 pp.

Caffey, D. L., 2006, Frank Springer and New Mexico: Texas A&M University Press, College Station, 261 pp.

Campbell, M. R., 1906, Survey work on coal during 1905: U.S. Geological Survey, Bulletin 285-F, pp. 203–210.

Campbell, M. R., 1907a, The Una del Gato coal field, Sandoval County, New Mexico: U.S. Geological Survey, Bulletin 316-F, pp. 427–430.

Campbell, M. R., 1907b, Coal in the vicinity of Fort Stanton Reservation, Lincoln County New Mexico: U.S. Geological Survey, Bulletin 316-F, pp. 431–434.

Chace, J., 2004, 1912: Simon and Shuster, New York, 323 pp.

Chamberlin, R. M., McLemore, V. T., Bowie, M. R., and Post, J. L., 1987, Roadlog from Socorro to Blue Canyon area of Socorro Peak, to US–60 clay pit, and to Luis Lopez manganese district; *in* McLemore, V. T., and Bowie, M. R. (comps.), Guidebook to the Socorro area, New Mexico: New Mexico Bureau of Mines and Mineral Resources, pp. 15–21.

Chamberlin, T. C., and Salisbury, R. D., 1906, Geology, vol. 2, Earth history: Henry Holt, New York, 692 pp.

Chapin, C. E., McIntosh, W. C., and Chamberlin, R. M., 2004, The late Eocene–Oligocene peak of Cenozoic volcanism in southwestern New Mexico; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Paper 11, pp. 271–293.

Christiansen, P. W., 1964, Of earth and sky: New Mexico Institute of Mining and Technology, Socorro, 107 pp.

Christiansen, P. W., 1974, The story of mining in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Scenic Trips to the Geologic Past, no. 12, 112 pp.

Coan, C. F., 1925, A history of New Mexico, v. 1: American Historical Society, Inc., Chicago and New York, 586 pp.

Cohen, S., 1986, Novels of New Mexico; *in* Williams, J. L., New Mexico in maps, 2nd edition: University of New Mexico Press, Albuquerque, pp. 353–356.

Condie, K. C., and Budding, A. J., 1979, Geology and geochemistry of Precambrian rocks, central and south-central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 35, 58 pp.

Connell, S. D., Hawley, J. W., and Love, D. W., 2005, Late Cenozoic drainage development in the southeastern basin and range of New Mexico, southeasternmost Arizona, and western Texas; *in* Lucas, S. G., Morgan, G. S., and Zeigler, K. E. (eds.), New Mexico's ice ages: New Mexico Museum of Natural History and Science, Bulletin 28, pp. 124–150.

Conrad, T. A., 1857, Descriptions of Cretaceous and Tertiary fossils; *in* Emory, W. H., Report on the United States and Mexican boundary survey: U.S. 34th Congress, 1st Session, Senate Executive Document 108 and House Executive Document 135, v. 1, pt. 2, pp. 141–174.

Cope, E. D., 1877, Report upon the extinct Vertebrata obtained in New Mexico by parties of the expedition of 1874: U.S. Geographical Surveys West of the 100th Meridian [Wheeler Survey], v. 4, pt. 2, 370 pp.

Cope, E. D., 1888, Synopsis of the vertebrate fauna of the Puerco series: Transactions of The American Philosophical Society, v. 16, pp. 291–361.

Cross, W., 1899, La Plata, Colorado: U.S. Geological Survey, Geologic Atlas, Folio 60.

Crumpler, L. S., and Aubele, J. C., 2001, Volcanoes of New Mexico: an abbreviated guide for non-specialists; *in* Crumpler, L. S., and Lucas, S. G., (eds.), Volcanology in New Mexico: New Mexico Museum of Natural History and Science, Bulletin 18, pp. 5–15.

Cummins, W. C., 1892, Notes on the geology of the country west of the plains: Geological Survey of Texas, 3rd Annual Report, pp. 201–223.

Dana, J. D., 1894, Manual of geology, fourth edition: American Book Co., New York, 1087 pp.

Darton, N. H., 1899, Preliminary report on the geology and water resources of Nebraska west of the 103rd meridian: U.S. Geological Survey, Annual Report 19, (1897–1898) pt. 4, Hydrography, pp. 719–785.

Darton, N. H., 1905, The Zuni salt lake: Journal of Geology, v. 13, pp. 185–193.

Darton, N. H., 1910, A reconnaissance of parts of northwestern New Mexico and orthern Arizona: U.S. Geological Survey, Bulletin 435, 88 pp.

Darton, N. H., 1916a, Geology and underground water of Luna County, New Mexico: U.S. Geological Survey, Bulletin 618, 188 pp.

Darton, N. H., 1916b, Guidebook of the western United States, Part C, the Santa Fe route: U.S. Geological Survey, Bulletin 613, 200 pp.

Darton, N. H., 1917a, A comparison of Paleozoic sections in southern New Mexico: U.S. Geological Survey, Professional Paper 108-C, pp. 31–55.

Darton, N. H., 1917b, Description of the Deming quadrangle: U.S. Geological Survey, Geologic Atlas, Deming Folio, no. 207, 15 pp.

Darton, N. H., 1928, "Red beds" and associated formations in New Mexico: U.S. Geological Survey, Bulletin 794, 356 pp.

Darton, N. H., and Burchard, E. F., 1911, Fluorspar near Deming, New Mexico: U.S. Geological Survey, Bulletin 470-K, pp. 533–545.

DuBois, S. M., and Smith, A. W., 1980, The 1887 earthquake in San Bernardino Valley, Sonora: historic accounts and intensity patterns in Arizona: Arizona Bureau of Geology and Mineral Technology, Special Paper no. 3, 112 pp.

Dunbar, C. O., and Rogers, J., 1957, Principles of stratigraphy: John Wiley & Sons, Inc., New York, 356 pp.

Dunbar, N. W., and Phillips, F. M., 2004, Cosmogenic ^{36}Cl ages of lava flows in the Zuni–Bandera volcanic field, north-central New Mexico, U.S.A.; *in* Cather, S. M., McIntosh, W. C., and Kelley, S. A., (eds.), Tectonics, geochronology, and volcanism in the Southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, pp. 309–317.

Dutton, C. E., 1885, Mount Taylor and the Zuni Plateau: U.S. Geological Survey, Annual Report 6 (1884–1885), pp. 105–198.

Eicher, D. L., 1976, Geologic time, 2nd edition: Prentice-Hall Inc., Englewood Cliffs, NJ, 150 pp.

Elston, W. E., 2001, The ignimbrite flareup in southwestern New Mexico: what have we learned these last 50 years?; *in* Crumpler, L. S., and Lucas, S. G., (eds.), Volcanology in New Mexico: New Mexico Museum of Natural History and Science, Bulletin 18, pp. 49–67.

Fisher, C. A., 1906, Preliminary report on the geology and underground waters in the Roswell artesian area, New Mexico: U.S. Geological Survey, Water-Supply Paper 158, 29 pp.

Fisk, D. M., 2003, American labor in the 20th century: U.S. Dept. of Labor web site.
Follansbee, R., Porter, E. A., Follett, W. W., and Gray, G. A., 1915, Water resources of the Rio Grande basin, 1888–1913: U.S. Geological Survey, Water-Supply Paper 358, 725 pp.
Frazier, A. H., and Heckler, W., 1972, Embudo, New Mexico, birthplace of systematic stream gaging: U.S. Geological Survey, Professional Paper 778, 23 pp.
Gardner, J., 1909a, The coal field between Gallina and Raton Spring, New Mexico, in the San Juan coal region: U.S. Geological Survey, Bulletin 341-C, pp. 335–351.
Gardner, J., 1909b, The coal field between Durango, Colorado, and Monero, New Mexico: U.S. Geological Survey, Bulletin 341-C, pp. 352–363.
Gardner, J., 1909c, The coal field between Gallup and San Mateo, New Mexico: U.S. Geological Survey, Bulletin 341-C, pp. 364–378.
Gardner, J., 1910a, Isolated coal fields in Santa Fe and San Miguel Counties, New Mexico: U.S. Geological Survey, Bulletin 381-C, pp. 447–451.
Gardner, J., 1910b, The Carthage coal field, New Mexico: U.S. Geological Survey, Bulletin 381-C, pp. 452–460.
Gardner, J., 1910c, The coal field between San Mateo and Cuba, New Mexico: U.S. Geological Survey, Bulletin 381-C, pp. 461–473.
Gardner, J., 1910d, The Puerco and Torrejon formations of the Nacimiento Group: Journal of Geology, v. 18, pp. 702–741.
Gidley, J. W., 1906, A new ruminant from the Pleistocene of New Mexico: Proceedings of the U.S. National Museum, v. 30, pp. 165–167.
Gilbert, G. K., 1875, Report on the geology of portions of New Mexico and Arizona examined in 1873: Report upon Geographical and Geological Explorations and Surveys West of the One Hundredth Meridian [Wheeler Survey], v. 3, Geology, pp. 507–567.
Gilmore, C. W., 1916, Vertebrate faunas of the Ojo Alamo, Kirtland, and Fruitland formations: U.S. Geological Survey, Professional Paper 98-Q, pp. 279–308.
Girty, G. H., 1902, The upper Permian in western Texas: American Journal of Science, 4th series, v. 14, pp. 363–368.
Girty, G. H., 1905, The relations of some Carboniferous faunas: Proceedings of the Washington Academy of Sciences, v. 7, pp. 1–26.
Girty, G. H., 1908, The Guadalupian fauna: U.S. Geological Survey, Professional Paper 58, 651 pp.
Girty, G. H., 1909, The Guadalupian fauna and new stratigraphic evidence: Annals of the New York Academy of Science, v. 19, no. 5, pt. 1, pp. 135–147.
Gordon, C. H., 1907a, Mississippian (Lower Carboniferous) formations of the Rio Grande valley, New Mexico: American Journal of Science, 4th series, v. 24, pp. 58–64.
Gordon, C. H., 1907b, Notes on the Pennsylvanian formations in the Rio Grande valley, New Mexico: Journal of Geology, v. 15, pp. 805–816.
Gordon, C. H., and Graton, L. C., 1906, Lower Paleozoic formations in New Mexico: American Journal of Science, 4th series, v. 23, pp. 390–395.
Gordon, C. H., and Graton, L. C., 1907, Lower Paleozoic formations in New Mexico: Journal of Geology, v. 15, pp. 91–92.
Gregg, J., 1844, Commerce of the prairies [M. L. Moorhead, ed.]: University of Oklahoma Press, Norman, 469 pp.
Gregory, H. E., 1916, The Navajo country; a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geological Survey, Water-Supply Paper 380, 219 pp.
Gregory, H. E., 1917, Geology of the Navajo country: U.S. Geological Survey, Professional Paper 93, 161 pp.
Hackett, O. M., 1964, The father of modern ground water hydrology: Ground Water, v. 2, no. 2, pp. 2–5.
Hall, J., 1856, Descriptions and notices of fossils collected upon the route; *in* Whipple, A. W., Report on explorations and surveys to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean, v. 3, pt. 4: U.S. 33rd Congress, 2nd Session, Senate Executive Document 78 and House Executive Document 91, pp. 99–105.
Hawley, J. W., 1993, Geomorphic setting and late Quaternary history of pluvial-lake basins in the southern New Mexico region: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 391, 28 pp.
Hawley, J. W., 2005, Five million years of landscape evolution in New Mexico: an overview based on two centuries of geomorphic conceptual-model development; *in* Lucas, S. G., Morgan, G. S., and Zeigler, K. E. (eds.), New Mexico's ice ages: New Mexico Museum of Natural History and Science, Bulletin 28, pp. 9–93.
Hawley, J. W., and Kernodle, J. M., 2008, Early contributions to arid-zone hydrogeology in the eastern Basin and Range region: Ground Water, v. 46, pp. 510–516.
Hay, O. P., 1902, Bibliography and catalogue of the fossil Vertebrata of North America: U.S. Geological Survey, Bulletin 179, 868 pp.
Hay, O. P., 1908, The fossil turtles of North America: Carnegie Institute of Washington, Publication 75, 568 pp.
Hay, O. P., 1910, Descriptions of eight new species of fossil turtles from west of the 100th meridian: Proceedings of the U.S. National Museum, v. 38, pp. 307–326.
Herrick, C. L., 1898a, The geology of the environs of Albuquerque: American Geologist, v. 22, pp. 26–43; Bulletin of the University of New Mexico, v. 1, pp. 25–43.
Herrick, C. L., 1898b, Papers on the geology of New Mexico: Denison University Scientific Laboratories Bulletin, v. 11, pp. 75–92; Bulletin of the University of New Mexico, v. 1, pp. 75–92.
Herrick, C. L., 1898c, The geology of the San Pedro and the Albuquerque districts: Denison University Scientific Laboratories Bulletin, v. 11, pp. 93–116; Bulletin of the University of New Mexico, v. 1, pp. 93–116.
Herrick, C. L., 1900a, Report of a geological reconnaissance in western Socorro and Valencia Counties, New Mexico: American Geologist, v. 25, pp. 331–346; Bulletin of the University of New Mexico, v. 2, 17 pp.
Herrick, C. L., 1900b, The geology of the White Sands of New Mexico: Journal of Geology, v. 8, pp. 112–128; Bulletin of the University of New Mexico, v. 2, 17 pp.
Herrick, C. L., 1904a, Laws of formation of New Mexico mountain ranges: American Geologist, v. 33, pp. 301–312, 393.
Herrick, C. L., 1904b, Lake Otero, an ancient salt lake basin in southeastern New Mexico: American Geologist, v. 34, pp. 174–189.
Herrick, C. L., and Johnson, D. W., 1900, The geology of the Albuquerque sheet: Denison University Scientific Laboratories Bulletin, v. 11, pp. 175–239; Bulletin of the University of New Mexico, v. 2, 67 pp.
Hill, R. T., 1891, Preliminary notes on the geology and topography of northern Mexico, southwest Texas, and New Mexico: American Geologist, v. 8, pp. 133–141.
Hill, R. T., 1892, Notes on the Texas–New Mexico region: Geological Society of America, Bulletin, v. 3, pp. 85–100.
Hill, R. T., 1893, On the occurrence of artesian and other underground waters in Texas, eastern New Mexico, and Indian Territory, west of the 97th meridian: U.S. 52nd Congress, Senate Executive Document 41, pt. 3, pp. 41–166.
Hill, R. T., 1900, Physical geography of the Texas region: U.S. Geological Survey, Topographical Atlas, Folio 3, 12 pp.
Hill, R. T., 1901, Geography and geology of the Black and Grand prairies, Texas: U.S. Geological Survey, Annual Report 21 (1899–1900), Pt. 7, 666 pp.
Hill, R. T., and Vaughan, T. W., 1898, The Lower Cretaceous gryphaeas of the Texas region: U.S. Geological Survey, Bulletin 151, 67 pp.
Hoffer, J. M., 1975, The Aden–Afton basalt, Potrillo volcanics, south-central New Mexico: Texas Journal of Science, v. 26, pp. 379–390.
Hoffer, J. M., Penn, B. S., Quezada, O. A., and Morales, M., 1998, Qualitative age relationships of late Cenozoic cinder cones, southern Rio Grande rift, utilizing cone morphology and Landsat thematic imagery: a preliminary assessment; *in* Mack, G. H., Austin, G. S., and Barker, J. M. (eds.), Las Cruces country II: New Mexico Geological Society, Guidebook 49, pp. 123–128.
Holmes, A., 1913, The age of the earth: Harper and Brothers, London and New York.
Holts, C. L., 1979, Fayette Jones, mining engineer—a profile in diversity: New Mexico Geology, v. 1, pp. 53–54, 63.
Hook, S. C., Molenaar, C. M., and Cobban, W. A., 1983, Stratigraphy and revision of nomenclature of upper Cenomanian to Turonian (Upper Cretaceous) rocks of west-central New Mexico; *in* Hook, S. C. (comp.), Contributions to mid- Cretaceous paleontology and stratigraphy of New Mexico—part II: New Mexico Bureau of Mines and Mineral Resouces, Circular 185, pp. 7–28.
Howard, J., 1993, Standing on sand: a short history of the Carlsbad area; *in* Love, D. W., Hawley, J. W., Kues, B. S., Adams, J. W., Austin, G. S., and Barker, J. M. (eds.), Carlsbad region, New Mexico and west Texas: New Mexico Geological Society, Guidebook 44, pp. 84–86.
Hufstetler, M., and Johnson, L., 1993, Watering the land: the turbulent history of the Carlsbad Irrigation District: National Park Service, Rocky Mountain Region, Division of National Preservation Programs, and Bureau of Reclamation, Upper Colorado Region, Denver, 170 pp.
Hyatt, A., 1903, Pseudoceratites of the Cretaceous: U.S. Geological Survey, Monograph 44, 351 pp.
Johnson, B. A., and Dauner, R. K. (eds.), 1981, Early Albuquerque: Albuquerque Journal, 270 pp.
Johnson, D. W., 1902, Notes of a geological reconnoissance [sic] in eastern Valencia County, New Mexico: The American Geologist, v. 29, pp. 80–87.
Johnson, D. W., 1902–1903, The geology of the Cerrillos Hills, New Mexico: Columbia School of Mines Quarterly, v. 24, pp. 173–246, 303–350, 456–500; v. 25, pp. 69–98.
Johnson, D. W., 1907, Volcanic necks of the Mount Taylor region, New Mexico: Geological Society of America, Bulletin, v. 18, pp. 303–324.
Johnston, B., 2011, History drive: Albuquerque Journal, Nov. 27, 2011, pp. E1, E5.
Jones, F. A., 1904, New Mexico mines and minerals: The New Mexico Printing Co., Santa Fe, 349 pp.
Julyan, R., 1996, The place names of New Mexico: University of New Mexico Press, Albuquerque, 385 pp.
Karlstrom, K. E., Amato, J. M., Williams, M. L., Heizler, M., Shaw, C. A., Read, A. S., and Bauer, P., 2004, Proterozoic tectonic evolution of the New Mexico region, a synthesis; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Paper 11, pp. 1–34.
Kelley, V. C., 1950, Regional structure of the San Juan Basin; *in* Kelley, V. C., Beaumont, E. C., and Silver, C. (eds.), San Juan Basin (New Mexico and Colorado): New Mexico Geological Society, Guidebook 1, pp. 101–108.
Kelley, V. C., 1952, Tectonics of the Rio Grande depression of central New Mexico; *in* Johnson, R. B., and Read, C. B. (eds.), Rio Grande country: New Mexico Geological Society, Guidebook 3, pp. 93–105.
Kelley, V. C., 1982, Albuquerque, its mountains, valley, water, and volcanoes: New Mexico Bureau of Mines and Mineral Resources, Scenic Trips to the Geologic Past, no. 9, 106 pp.
Kelley, V. C., and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 156, 30 pp.
Keyes, C. R., 1903, Geological formations of New Mexico; *in* Report of the Governor of New Mexico to the Secretary of the Interior, 1903: Washington, pp. 337–341.
Keyes, C. R., 1904, Bolson plains and the conditions of their existence: American Geologist, v. 34, pp. 160–164.

Keyes, C. R., 1906, Physiography of New Mexico: Journal of Geography, v. 5, pp. 251–256.
Kindle, E. M., 1909, The Devonian fauna of the Ouray limestone: U.S. Geological Survey, Bulletin 391, 60 pp.
King, P. B., 1949, Memorial to Nelson Horatio Darton: Geological Society of America, Annual Report for 1948, Proceedings Volume, pp. 146–170.
Klein, A., 2009, Personal income of U.S. states: estimates for the period 1880–1910: Warwick Economic Research papers, no. 916, 61 pp.
Knowlton, F. H., 1889, New species of fossil wood (*Araucarioxylon arizonicum*) from Arizona and New Mexico: U.S. National Museum, Proceedings, v. 11, pp. 1–4.
Knowlton, F. H., 1913, Results of a paleobotanical study of the coal-bearing rocks of the Raton Mesa region of Colorado and New Mexico: American Journal of Science, 4th series, v. 35, pp. 526–539.
Knowlton, F. H., 1916, Contributions to the geology and paleontology of San Juan County, New Mexico; 4, Flora of the Fruitland and Kirtland formations: U.S. Geological Survey, Professional Paper 98-S, pp. 327–353.
Knowlton, F. H., 1917, Fossil floras of the Vermejo and Raton formations of Colorado and New Mexico: U.S. Geological Survey, Professional Paper 101, pp. 223–435.
Kottlowski, F. E., 1965, Coal; *in* Mineral and water resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 87, pp. 100–116.
Kues, B. S., 1985a, Early geological explorations in northeastern and east-central New Mexico; *in* Lucas, S. G., and Zidek, J. (eds.), Santa Rosa–Tucumcari region: New Mexico Geological Society, Guidebook 36, pp. 103–118.
Kues, B. S., 1985b, Stratigraphy of the Tucumcari area: a historical account; *in* Lucas, S. G., and Zidek, J. (eds.), Santa Rosa–Tucumcari region: New Mexico Geological Society, Guidebook 36, pp. 119–140.
Kues, B. S., 1986, Paleontology of the Caballero and Lake Valley Formations (Lower Mississippian) west of the Rio Grande, south-central New Mexico; *in* Clemons, R. E., King, W. E., Mack, G. H., and Zidek, J. (eds.), Truth or Consequences region: New Mexico Geological Society, Guidebook 37, pp. 203–214.
Kues, B. S., 1992, James Hervey Simpson and the first record of San Juan Basin geology; *in* Lucas, S. G., Kues, B. S., Williamson, T. E., and Hunt, A. P. (eds.), San Juan Basin IV: New Mexico Geological Society, Guidebook 43, pp. 83–101.
Kues, B. S., 1993, Bibliographic catalogue of New Mexico vertebrate fossils: New Mexico Museum of Natural History and Science, Bulletin 2, pp. 199–279.
Kues, B. S., 2006, Geological studies of the Guadalupe Mountains area, New Mexico and west Texas, to 1928; *in* Land, L., Lueth, V. W., Raatz, W., Boston, P., and Love, D. W. (eds.), Caves and karst of southeastern New Mexico: New Mexico Geological Society, Guidebook 57, pp. 127–144.
Kues, B. S., 2008a, Early geological studies in southwestern and south-central New Mexico; *in* Mack, G., Witcher, J., and Lueth, V. W. (eds.), Geology of the Gila Wilderness–Silver City area: New Mexico Geological Society, Guidebook 59, pp. 77–106.
Kues, B. S., 2008b, The paleontology of New Mexico: University of New Mexico Press, Albuquerque, 428 pp.
Lee, W. T., 1902, The Morrison shales of southern Colorado and northern New Mexico: Journal of Geology, v. 10, pp. 36–58.
Lee, W. T., 1903, The canyons of northeastern New Mexico: Journal of Geography, v. 2, pp. 63–82.
Lee, W. T., 1906, The Engle coal field, New Mexico: U.S. Geological Survey, Bulletin 285-F, p. 240.
Lee, W. T., 1907a, Note on the red beds of the Rio Grande region in central New Mexico: Journal of Geology, v. 15, pp. 52–58.
Lee, W. T., 1907b, Water resources of the Rio Grande valley in New Mexico, and their development: U.S. Geological Survey, Water-Supply Paper 188, 59 pp.
Lee, W. T., 1907c, Afton craters of southern New Mexico: Geological Society of America, Bulletin, v. 18, pp. 211–220.
Lee, W. T., 1908, Notes on the lower Paleozoic rocks of central New Mexico: American Journal of Science, 4th series, v. 26, pp. 180–186.
Lee, W. T., 1909, Unconformity in the so-called Laramie of the Raton coal field: Geological Society of America, Bulletin, v. 20, pp. 357–358.
Lee, W. T., 1912a, Stratigraphy of the coal fields of northern central New Mexico: Geological Society of America, Bulletin, v. 23, pp. 571–686.
Lee, W. T., 1912b, The Tijeras coal field, Bernalillo County, New Mexico: U.S. Geological Survey, Bulletin 471-H, pp. 575–578.
Lee, W. T., 1912c, Extinct volcanoes of northeast New Mexico: American Forestry, v. 18, pp. 357–365.
Lee, W. T., 1913a, The Cerrillos coal field, Santa Fe County, New Mexico: U.S. Geological Survey, Bulletin 531-J, pp. 285–312.
Lee, W. T., 1913b, Recent discovery of dinosaurs in the Tertiary: American Journal of Science, 4th series, v. 35, pp. 531–534.
Lee, W. T., 1915, Relation of the Cretaceous formations to the Rocky Mountains in Colorado and New Mexico: U.S. Geological Survey, Professional Paper 95-C, pp. 27–58.
Lee, W. T., 1917a, General stratigraphic break between Pennsylvanian and Permian in western North America: Geological Society of America, Bulletin, v. 28, pp. 169–170.
Lee, W. T., 1917b, Geology of the Raton Mesa and other regions in Colorado and New Mexico: U.S. Geological Survey, Professional Paper 101, pp. 9–221.
Lee, W. T., 1918, Early Mesozoic physiography of the southern Rocky Mountains: Smithsonian Miscellaneous Collections, v. 69, no. 4, pp. 1–41.
Lee, W. T., and Girty, G. H., 1909, The Manzano group of the Rio Grande valley, New Mexico: U.S. Geological Survey, Bulletin 389, 141 pp.
Lehman, T. M., 1994, The saga of the Dockum Group and the case of the Texas/New Mexico boundary fault; *in* Ahlen, J., Peterson, J., Bowsher, A. L., and Zidek, J. (eds.), Geologic activities in the 90s, Southwest Section of the AAPG 1994, Ruidoso, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 150, pp. 37–51.
Lindgren, W., and Graton, L. C., 1906, A reconnaissance of the mineral deposits of New Mexico: U.S. Geological Survey, Bulletin 285, pp. 74–86.
Lindgren, W., Graton, L. C., and Gordon, C. H., 1910, The ore deposits of New Mexico: U.S. Geological Survey, Professional Paper 68, 361 pp.
Lloyd, E. R., 1929, Capitan Limestone and associated formations of New Mexico and Texas: American Association of Petroleum Geologists, Bulletin, v. 13, pp. 645–658.
Long, R. A., and Murry, P.A., 1995, Late Triassic (Carnian and Norian) tetrapods from the southwestern United States: New Mexico Museum of Natural History and Science, Bulletin 4, 254 pp.
Love, J. C., 2006, In memory of Christina Lochman-Balk, 1907–2006: New Mexico Geology, v. 28, pp. 88–90.
Lucas, S. G., 2003, Clarence Dutton's stratigraphy of west-central New Mexico; *in* Lucas, S. G., Semken, S. C., Berglof, W. R., and Ulmer-Scholle, D. S. (eds.), Geology of the Zuni Plateau: New Mexico Geological Society, Guidebook 54, pp. 209–217.
Lucas, S. G., 2004, The Triassic and Jurassic Systems in New Mexico; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, pp. 137–152.
Lucas, S. G., and Hawley, J. W., 2002, The Otero Formation, Pleistocene lacustrine strata in the Tularosa Basin, southern New Mexico; *in* Lueth, V. W., Giles, K. A., Lucas, S. G., Kues, B. S., Myers, R., and Ulmer-Scholle, D. S. (eds.), Geology of White Sands: New Mexico Geological Society, Guidebook 53, pp. 277–283.
Lucas, S. G., Mack, G. H., and Estep, J., 1998, The ceratopsian dinosaur *Torosaurus* from the Upper Cretaceous McRae Formation, Sierra County, New Mexico; *in* Mack G. H., Austin, G. S., and Barker, J. M. (eds.), Las Cruces country part II: New Mexico Geological Society, Guidebook 49, pp. 223–227.
Lucas, S. G., Zeigler, K. E., and Spielmann, J. A. (eds.), 2005, The Permian of central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 31, 176 pp.
Mack, G. H., 2004, Middle and late Cenozoic crustal extension, sedimentation, and volcanism in the southern Rio Grande rift, Basin and Range, and southern Transition zone of southwestern New Mexico; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, pp. 389–406.
Mack, G. H., Witcher, J., and Lueth, V. W., 2008, Precambrian, Paleozoic, Cretaceous, and early Cenozoic stratigraphy of the Silver City area; *in* Mack, G., Witcher, J., and Lueth, V. W. (eds.), Geology of the Gila Wilderness–Silver City area: New Mexico Geological Society, Guidebook 59, back end sheet.
Marcou, J., 1858, Geology of North America, with two reports on the prairies of Arkansas and Texas, the Rocky Mountains of New Mexico, and the Sierra Nevada of California, originally made for the United States government: Zurich, Zurcher and Furrer, 144 pp.
Marsh, O. C., 1878, Notice of new fossil reptiles: American Journal of Science, 3rd series, v. 15, pp. 409–411.
Matthew, W. D., 1899, A provisional classification of the fresh-water Tertiary of the West: American Museum of Natural History, Bulletin, v. 12, pp. 19–77.
Matthew, W. D., 1937, Paleocene faunas of the San Juan Basin, New Mexico: Transactions of the American Philosophical Society, v. 30, 510 pp.
Maxey, G. B., 1979, The Meinzer era of U.S. hydrogeology, 1910–1940: Journal of Hydrology, v. 43, pp. 1–6.
Maxwell, C. H., 1982, El Malpais; *in* Wells, S. G., Grambling, J. A., and Callender, J. F. (eds.), Albuquerque country II: New Mexico Geological Society, Guidebook 33, pp. 299–301.
McAllister, P. E., and Putman, M. L., 1986, Communications: telephone; *in* Williams, J. L. (ed.), New Mexico in maps, 2nd edition: University of New Mexico Press, Albuquerque, pp. 304–306.
McMillan, N. J., 2004, Magmatic record of Laramide subduction and the transition to Tertiary extension: Upper Cretaceous through Eocene igneous rocks of New Mexico; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, pp. 249–270.
Means, T. H., and Gardner, F. D., 1900, A soil survey in the Pecos Valley, New Mexico: Division of Soils Field Operations Report 64, pp. 36–76.
Meek, F. B., 1876, Descriptions of the Cretaceous fossils collected on the San Juan exploring expedition under Capt. J. N. Macomb, U.S. Engineers; *in* Macomb, J. N. (ed.), Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green Rivers of the great Colorado of the West, in 1859: Washington, Engineers Department, U.S. Army, pp. 119–133.
Meinzer, O. E., 1911, Geology and water resources of Estancia valley, New Mexico: U.S. Geological Survey, Water-Supply Paper 275, 89 pp.
Meinzer, O. E., and Hare, R. F., 1915, Geology and water resources of the Tularosa Basin, New Mexico: U.S. Geological Survey, Water-Supply Paper 343, 317 pp.
Merrill, G. P., 1924, The first one hundred years of American geology: Yale University Press, New Haven, 773 pp.
Morgan, V. L., and Lucas, S. G., 2002, Walter Granger, 1872–1941, paleontologist: New Mexico Museum of Natural History and Science, Bulletin 19, 58 pp.
Muehlberger, W. R., Muehlberger, S. J., and Price, L. G., 2010, Capulin Volcano National Monument; *in* Price, L. G. (ed.), The geology of northern New Mexico's parks, monuments, and public lands: New Mexico Bureau of Geology and Mineral Resources, pp. 313–318.

Mueller, J. E., 1986, History of Elephant Butte Dam and Reservoir; *in* Clemons, R. E., King, W. E., and Mack, G. H. (eds.), Truth or Consequences region: New Mexico Geological Society, Guidebook 37, pp. 58–59.
Myrick, D. F., 1970, New Mexico railroads—an historical survey: Colorado Railroad Museum, Golden, 205 pp.
Newberry, J. S., 1861, Geological report; *in* Ives, J. C., Report upon the Colorado River of the West: U.S. 36th Congress, First Session, Senate Executive Document 77 and House Executive Document 90, 154 pp.
Newberry, J. S., 1876, Geological report; *in* Macomb, J. N. (ed.), Report of the exploring expedition from Santa Fe, New Mexico, to the junction of the Grand and Green Rivers of the great Colorado of the West in 1859: Washington, D.C., Engineer Dept., U. S. Army, 118 pp.
Northrop, S. A., 1966, University of New Mexico contributions in geology, 1898–1964: University of New Mexico, Publications in Geology, no. 7, 152 pp.
Northrop, S. A., 1982, Earthquakes of Albuquerque country; *in* Grambling, J. A., and Wells, S. G. (eds.), Albuquerque country II: New Mexico Geological Society, Guidebook 33, pp. 171–178.
Nymeyer, R., and Halliday, W. R., 1991, Carlsbad Cavern, the early years: Carlsbad Caverns–Guadalupe Mountains Association, Carlsbad, New Mexico, 156 pp.
Ogilvie, I. H., 1902, An analcite-bearing camptonite from New Mexico: Journal of Geology, v. 10, pp. 500–507.
Ogilvie, I. H., 1905, The high-altitude conoplain: a topographic form illustrated in the Ortiz Mountains: American Geologist, v. 36, pp. 27–34.
Ogilvie, I. H., 1908, Some igneous rocks from the Ortiz Mountains, New Mexico: Journal of Geology, v. 16, pp. 230–238.
Paige, S., 1909, The Hanover iron-ore deposits, New Mexico: U.S. Geological Survey, Bulletin 380-E, pp. 199–214.
Paige, S., 1911a, The ore deposits near Pinos Altos, New Mexico: U.S. Geological Survey, Bulletin 470-B pp. 109–125.
Paige, S., 1911b, Metalliferous ore deposits near the Burro Mountains, Grant County, New Mexico: U.S. Geological Survey, Bulletin 470-C, pp. 131–150.
Paige, S. 1912a, The geologic and structural relations at Santa Rita (Chino), New Mexico: Economic Geology, v. 7, pp. 547–449.
Paige, S. 1912b, The origin of turquoise in the Burro Mountains, New Mexico: Economic Geology, v. 7, pp. 383–392.
Paige, S., 1916, Description of the Silver City quadrangle, New Mexico: U.S. Geological Survey, Geologic Atlas, Silver City Folio, no. 199, 19 pp.
Powell, J. W., 1895, Physiographic regions of the United States: National Geographic Society, Monograph 3, pp. 65–100.
Rabbitt, M. C., 1989, The United States Geological Survey, 1879–1989: U.S. Geological Survey, Circular 1050, 52 pp.
Reeside, J. B., Jr., 1924, Upper Cretaceous and Tertiary formations of the western part of the San Juan Basin of Colorado and New Mexico: U.S. Geological Survey, Professional Paper 134, pp. 1–70.
Reeve, F. D., 1961, History of New Mexico: Lewis Historical Publishing Co., New York, v. 2, 449 pp.
Rex, H., 1986, Library collections; *in* Williams, J. L. (ed.), New Mexico in maps, 2nd edition: University of New Mexico Press, Albuquerque, pp. 360–362.
Richardson, G. B., 1904, Report of a reconnaissance in trans-Pecos Texas, north of the Texas and Pacific Railway: Texas University Mineral Survey, Bulletin 9, 119 pp.
Richardson, G. B., 1908, Paleozoic formations in trans-Pecos Texas: American Journal of Science, 4th series, v. 25, pp. 474–484.
Richardson, G. B., 1909, Description of the El Paso district: U.S. Geological Survey, Geologic Atlas, Folio 166, 11 pp.
Richardson, G. B., 1910, Stratigraphy of the upper Carboniferous in west Texas and southeast New Mexico: American Journal of Science, 4th series, v. 29, pp. 325–337.
Robertson, E. C., (ed.), 1993, Centennial history of the Geological Society of Washington, 1893–1993: Geological Society of Washington, Washington, D.C., 165 pp.
Salisbury, R. D., 1901, Glacial work in the western mountains in 1901: Journal of Geology, v. 9, pp. 718–731.
Sanford, A. R., 1963, Seismic activity near Socorro; *in* Kuellmer, F. J. (ed.), Guidebook of the Socorro region, New Mexico: New Mexico Geological Society, Guidebook 14, pp. 146–151.
Sanford, A. R., 1983, Magma bodies in the Rio Grande rift in central New Mexico; *in* Chapin, C. E., and Callender, J. F. (eds.), Socorro region II: New Mexico Geological Society, Guidebook 34, pp. 123–125.
Schrader, F. C., 1906, The Durango–Gallup coal field of Colorado and New Mexico: U.S. Geological Survey, Bulletin 285-F, pp. 241–258.
Schuchert, C., 1924, A text-book of geology, Part II, historical geology: John Wiley & Sons, New York, 724 pp.
Seager, W. R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 36, 97 pp.
Seager, W. R., 1987, Caldera-like collapse at Kilbourne Hole, New Mexico: New Mexico Geology, v. 9, pp. 69–73.
Seager, W. R., 2004, Laramide (Late Cretaceous–Eocene) tectonics of southwestern New Mexico; *in* Mack, G. H., and Giles, K. A. (eds.), The geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, pp. 183–202.
Sears, J. D., Hunt, C. B., and Hendricks, T. A., 1941, Transgressive and regressive Cretaceous deposits in southern San Juan Basin, New Mexico: U.S. Geological Survey, Professional Paper 193-F, pp. 101-121.
Shaler, M. K., 1907, A reconnaissance survey of the western part of the Durango–Gallup coal field of Colorado and New Mexico: U.S. Geological Survey, Bulletin 316-F, pp. 376–426.
Shimer, H. W., and Blodgett, M. E., 1908, The stratigraphy of the Mt. Taylor region, New Mexico: American Journal of Science, 4th series, v. 25, pp. 53–67.
Shumard, G. G., 1858, Observations on the geological formations of the country between the Rio Pecos and Rio Grande, near the line of the 32nd parallel: St. Louis Academy of Sciences, Transactions, v. 1, pp. 273–289.
Shumard, G. G., 1859, The geological structure of the "Jornada del Muerto," New Mexico: St. Louis Academy of Sciences, Transactions, v. 1, pp. 341–355.
Silliman, B., Jr., 1880, Rio Grande gold gravels: report on the newly discovered auriferous gravels of the upper Rio Grande del Norte in the counties of Taos and Rio Arriba, New Mexico: Henry Gibson, Herald Publishing House, Omaha, Nebraska, 34 pp.
Simmons, M., 1982, Albuquerque, a narrative history: University of New Mexico Press, Albuquerque, 443 pp.
Simpson, G. G., 1948, The Eocene of the San Juan Basin, New Mexico: American Journal of Science, v. 246, pp. 257–282, 363–385.
Simpson, G. G., 1959, Fossil mammals from the type area of the Puerco and Torrejon strata, Paleocene of New Mexico: American Museum Novitates, no. 1957, 22 pp.
Simpson, J. H., 1850, Report from the Secretary of War communicating the report of Lieutenant J. H. Simpson of an expedition into the Navajo country in 1849, and, also, the report of Captain S. G. French relative to the road opened between San Antonio and El Paso del Norte: U.S. 31st Congress, First Session, Senate Executive Document 64, pp. 55–138, 146–148.
Sinclair, U., 1906, The jungle: Doubleday, Page & Co., New York, 475 pp.
Sinclair, W. J., and Granger, W., 1914, Paleocene deposits of the San Juan Basin, New Mexico: American Museum of Natural History, Bulletin, v. 33, pp. 297–316.
Slichter, C. S., 1905, Observations on ground waters of the Rio Grande valley: U.S. Geological Survey, Water-Supply and Irrigation Paper 141, 83 pp.
Smith, C. T., Osburn, G. R., Chapin, C. E., Hawley, J. W., Osburn, J. C., Anderson, O. J., Rosen, S. D., Eggleston, T. L., and Cather, S. M., 1983, First day road log from Socorro to Mesa del Yeso, Joyita Hills, Johnson Hill, Cerros de Amado, Lomas de las Canas, Jornada del Muerto, Carthage, and return to Socorro; *in* Chapin, C. E., and Callender, J. F. (eds.), Socorro region II: New Mexico Geological Society, Guidebook 34, pp. 1–28.
Springer, A., 1902, On some living and fossil snails of the genus *Physa*, found at Las Vegas, New Mexico: Philadelphia Academy of Natural Sciences Proceedings, v. 54, pp. 513–516.
Springer, F., 1884, On the occurrence of the lower Burlington Limestone in New Mexico: American Journal of Science, 3rd series, v. 27, pp. 97–103.
Stanton, T. W., 1893, The Colorado Formation and its invertebrate fauna: U.S. Geological Survey, Bulletin 106, 288 pp.
Stanton, T. W., 1905, The Morrison Formation and its relations with the Comanche Series and the Dakota Formation: Journal of Geology, v. 13, pp. 657–669.
Statesman's Yearbook, 1913, MacMillan & Co., London, 1536 pp.
Statistical Abstracts of the United States, 1913, U.S. Government Printing Office, Washington, 720 pp.
Stevenson, J. J., 1881, Report upon geological examinations in southern Colorado and northern New Mexico during the years 1878 and 1879: U.S. Geographical Surveys West of the One-Hundredth Meridian [Wheeler Survey], v. 3, supplement–geology, 420 pp. Storrs, L. S., 1902, The Rocky Mountain coal fields: U.S. Geological Survey, Annual Report 22 (1900–1901), pt. 3, pp. 415–471.
Stone, W. J., 2001, Our water resources, an overview for New Mexicans: New Mexico Bureau of Mines and Mineral Resources, 37 pp.
Storrs, L. S., 1902, The Rocky Mountain coal fields: U.S. Geological Survey, Annual Report 22 (1900–1901), pt. 3, pp. 415–471.
Stringfield, V. T., 1974, Oscar Edward Meinzer; *in* Dictionary of scientific biography, v. 9: Charles Scribners Sons, New York, pp. 257–258.
Summers, W. K., 1976, Catalog of thermal waters in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 4, 80 pp.
Tarr, R. S., 1890, Drainage systems of New Mexico: American Geologist, v. 5, pp. 261–270.
Thornbury, W. D., 1965, Regional geomorphology of the United States: John Wiley & Sons, New York, 609 pp.
Tight, W. G., 1905, Bolson plains of the Southwest: American Geologist, v. 36, pp. 271–284.
Twitchell, R. E., 1917, The leading facts of New Mexico history, vol. V: The Torch Press, Cedar Rapids, 505 pp.
Vieyra, D. I., 1979, Fill'er up, an architectural history of America's gas stations: Collier Books, New York, 111 pp.
Vigil-Giron, R., 2005, New Mexico bluebook, 2005–2006: Office of the Secretary of State, Santa Fe, 372 pp.
Wachsmuth, C., and Springer, F., 1897, The North American Crinoidea Camerata: Harvard College, Museum of Comparative Zoology, Memoir 20-21, 837 pp.
Weber, R. H., and Bassett, W. A., 1963, K-Ar ages of Tertiary volcanic and intrusive rocks in Socorro, Catron, and Grant Counties, New Mexico; *in* Kuellmer, F. J. (ed.), Guidebook of the Socorro region, New Mexico: New Mexico Geological Society, Guidebook 14, pp. 220–223.
Wegener, A., 1929, The origin of continents and oceans [translated by J. Biram]: Dover Press, New York, (1966), 246 pp.
White, C. A., 1881, Report on the Carboniferous invertebrate fossils of New Mexico: U.S. Geographical Surveys West of the One Hundredth Meridian [Wheeler Survey], v. 3, supplement—geology, Appendix, 38 pp.

Williams, J. L., 1986a, Surveyors and homesteaders, 1880–1940; *in* Williams, J. L. (ed.), New Mexico in maps, 2nd edition: University of New Mexico Press, Albuquerque, pp. 126–128.

Williams, J. L., 1986b, Communications: radio; *in* Williams, J. L. (ed.), New Mexico in maps, 2nd edition: University of New Mexico Press, Albuquerque, pp. 298–300.

Williams, J. L., 1986c, Movies made in New Mexico; *in* Williams, J. L., (ed.), New Mexico in maps, 2nd edition: University of New Mexico Press, Albuquerque, pp. 350–352.

Williams, J. S., 1940, Memorial to George Herbert Girty: Proceedings of the Geological Society of America for 1939, pp. 195–205.

Williston, S. W., 1911, American Permian vertebrates: University of Chicago Press, Chicago, 144 pp.

Wood, E. A., 1964, Memorial to Ida Helen Ogilvie (1874–1963): Geological Society of America, Bulletin, v. 75, p. 35–40.

World Almanac and Encyclopedia, 1912, The Press Publishing Co., New York, 800 pp.

Wright Dunbar, R., Zech, R. S., Crandall, G. A., and Katzman, D., 1992, Strandplain and deltaic depositional models for the Point Lookout Sandstone, San Juan Basin and Four Corners platform, New Mexico and Colorado; *in* Lucas, S. G., Kues, B. S., Williamson, T. E., and Hunt, A. P. (eds.), San Juan Basin IV: New Mexico Geological Society, Guidebook 43, pp. 199–206.