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Celebrating New Mexico's Centennial

The geology of New Mexico as understood in 1912: an essay for the centennial of New Mexico statehood Part 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. 41). 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.
Cenozoic (recent life).	Quaternary.	Recent. Pleistocene (Great Ice Age).	"Age of man." Animals and plants of modern types.	*Millions of years.* 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

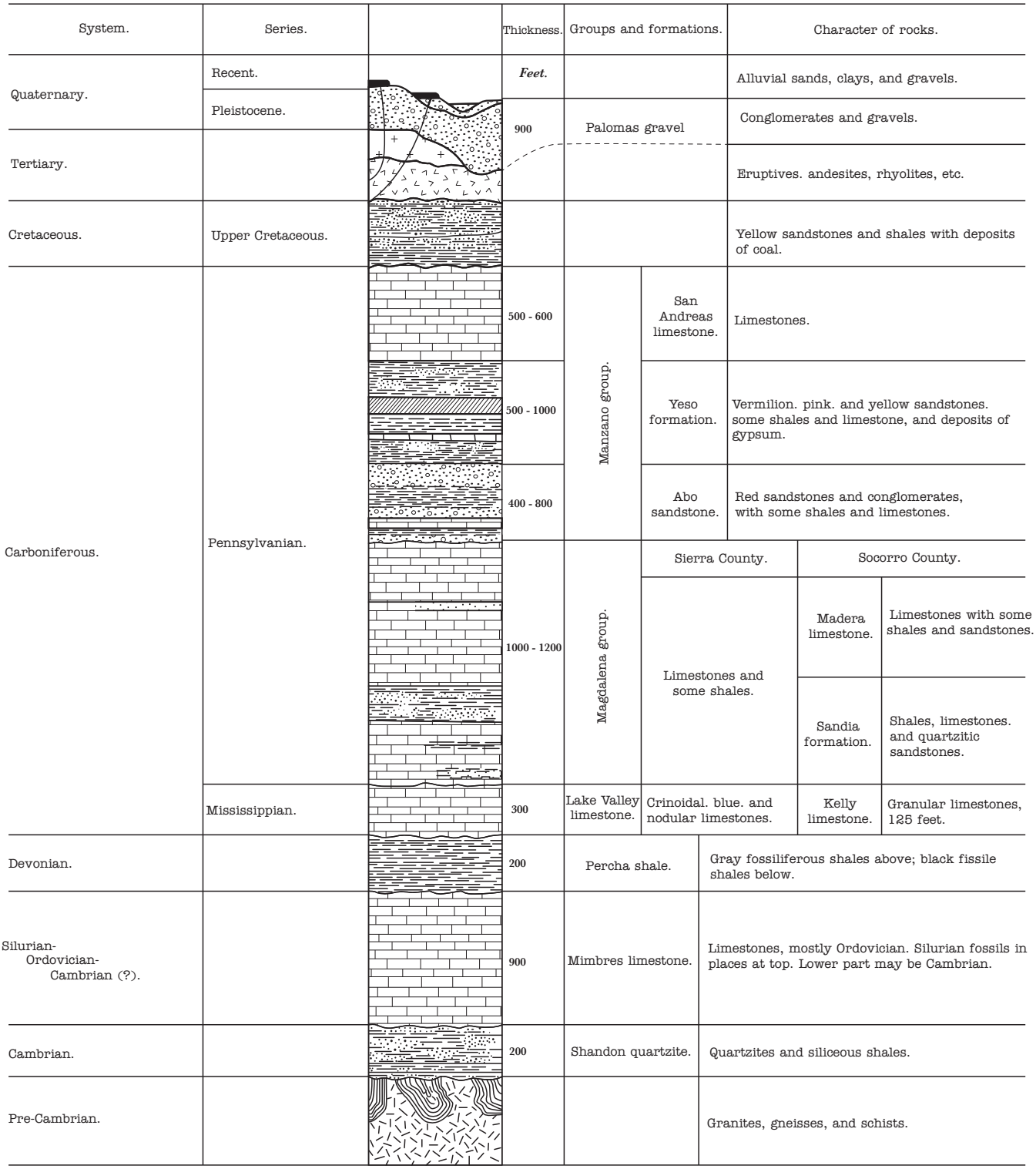

FIGURE 6—Stratigraphic units exposed in central and southern New Mexico, as understood around 1912 (redrawn from Lindgren et al. 1910). The thickness of these units is accurate for the area around the Chino mine, but the thickness of the Cenozoic volcanic section increases greatly in all directions,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

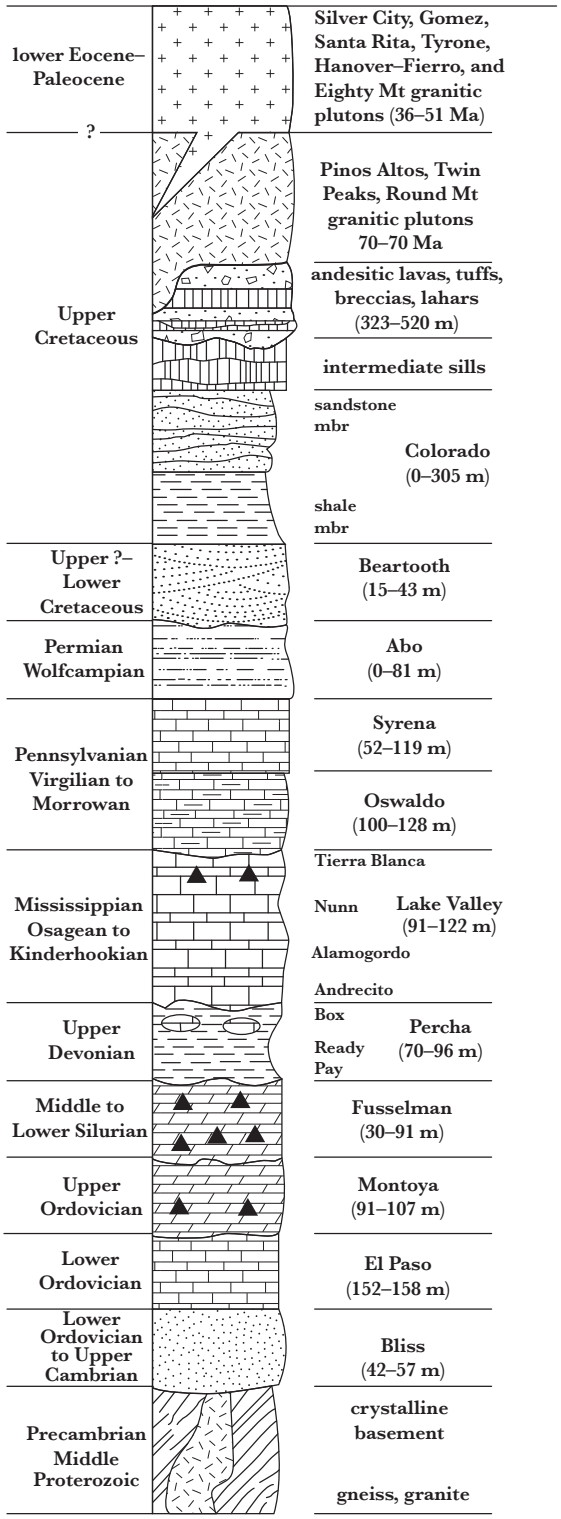

FIGURE 7—Modern stratigraphy of the Silver City area (modified from Mack et al. 2008). The Colorado Formation is a southern expression of the Mancos Shale, and the Beartooth is correlated with the Mojado or Sarten Formations by some stratigraphers.

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

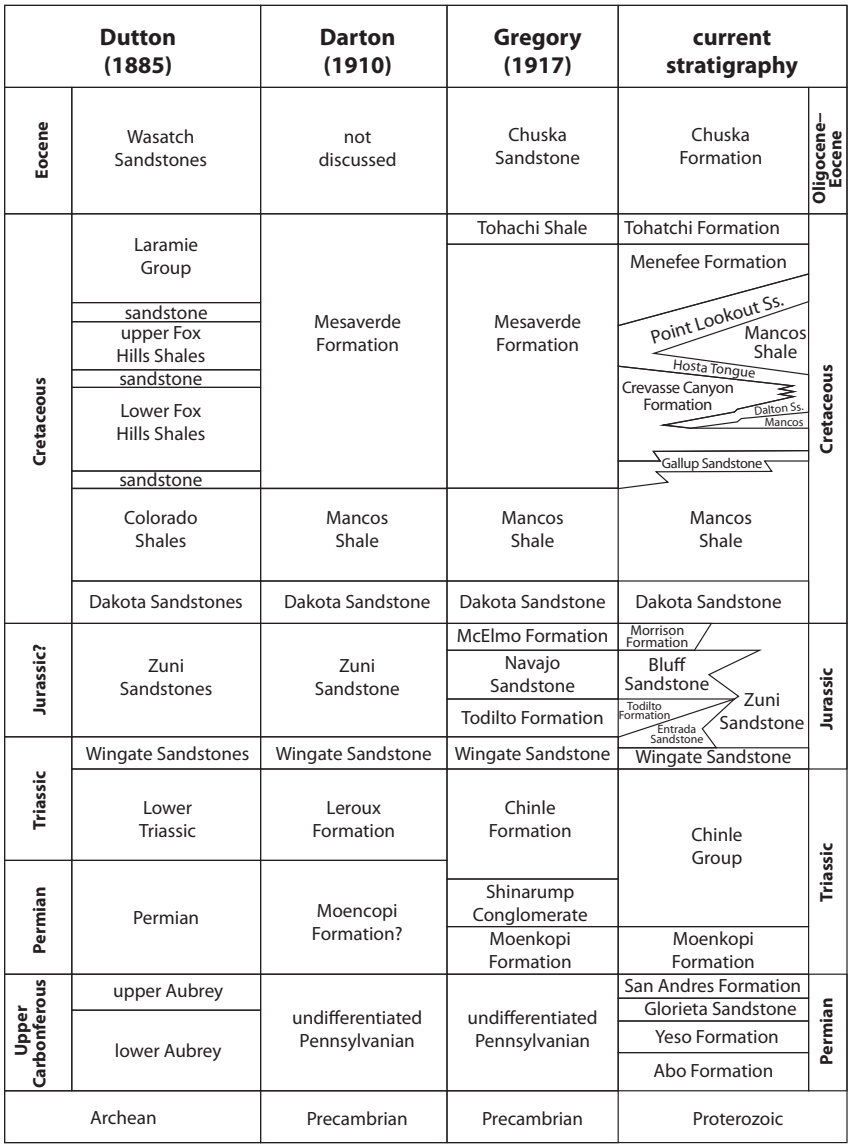

FIGURE 9—Dutton's (1885) stratigraphy of west-central New Mexico, and revisions to the present (modified from Lucas 2003, fig. 8).

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

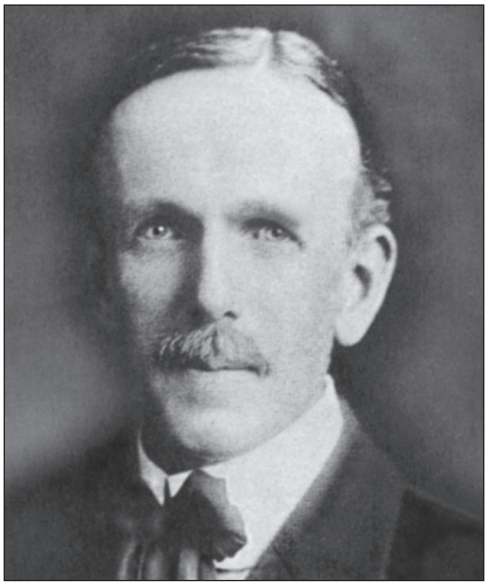

FIGURE 10—N. H. Darton, USGS (King 1949).

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

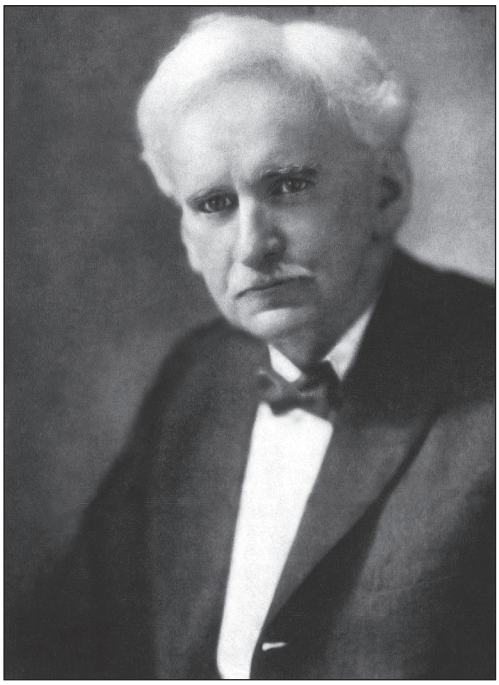

FIGURE 11—Willis T. Lee, USGS (Alden 1926).

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. 38) 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. 34), 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. 31–32). 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)

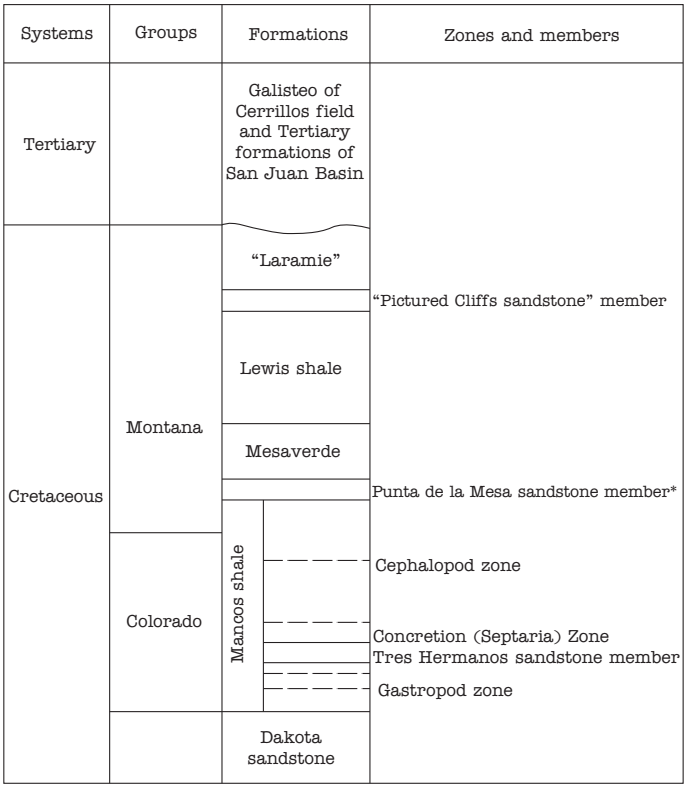

FIGURE 12—Upper Cretaceous stratigraphic units recognized in 1912 (redrawn from Lee 1912a).

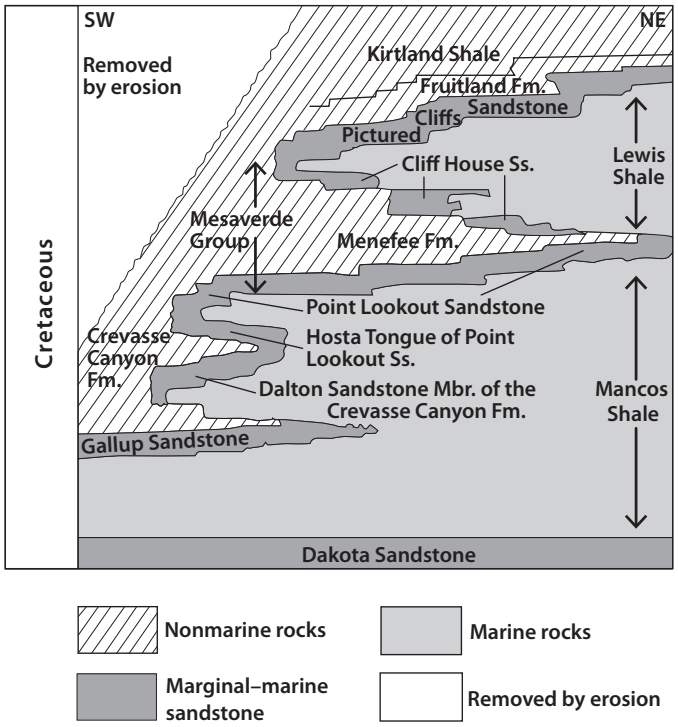

FIGURE 13—Generalized modern Late Cretaceous stratigraphy of the San Juan Basin (modified from Wright Dunbar et al. 1992), showing transgressive-regressive nature of the stratigraphic units, which would begin to be recognized soon after New Mexico became a state.

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. 38). 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

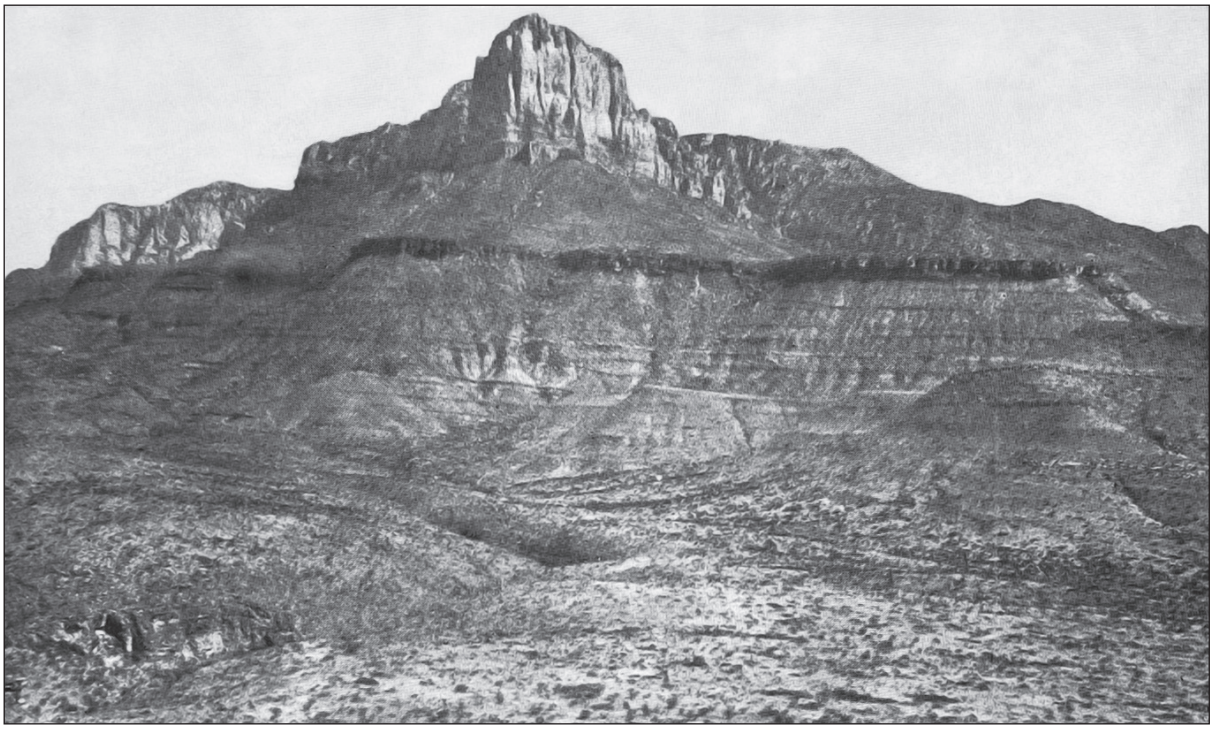

FIGURE 14—South end of the Guadalupe Mountains, source of Girty's (1908) prolific Permian faunas (Richardson 1904, pl. 4A).

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. 32). 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. 38), 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. 36). 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.

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