The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—New Mexico

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Historical review and summary of
areal, stratigraphic, structural,
and economic geology of Mississippian
and Pennsylvanian rocks in New Mexico

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THE MISSISSIPPIAN AND PENNSYLVANIAN (CARBONIFEROUS) SYSTEMS IN THE UNITED STATES—NEW MEXICO

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ABSTRACT

Initial Lower Mississippian deposits of New Mexico are Tournaisian (pre-Zone 7) in age and are unconformable on older rocks of Late Devonian or Precambrian age. These Mississippian rocks were laid down during transgression of the sea across an abraded surface of very low relief. Early and middle Tournaisian marine transgression began in the southwestern and south-central part of the State and deposited the Keating (207 m), Caballero (18 m), and Lake Valley (180 m) Formations on a carbonate platform. By the end of Tournaisian (Osagean) time, epicontinental seas had flooded the central and northern part of the State and had deposited the Kelly Limestone (35 m) and Espiritu Santo Formation. The latter is a sequence of subtidal to supratidal quartz sandstones and carbonate rocks. Leadville Limestone (50–100 m) in the San Juan Basin is a time-stratigraphic equivalent to the Espiritu Santo Formation (35 m) and is an eastern extension of part of the Redwall Limestone of Arizona. The Zuni Highlands and remnants of the transcontinental arch, the Pedernal Highlands, were two low islands. The end of Tournaisian (Osagean) time was marked by marine regression, regional uplift, and erosion of Tournaisian carbonate sedimentary deposits.

A major regional marine transgression took place in Viséan (Meramecian) time and is represented by the massive encrinites of the Hachita Formation (107 m) in southwestern New Mexico, the deeper water basin carbonate rocks of the lower part of the Rancheria Formation (46 m) in south-central New Mexico, and part of the Tererro Formation (18 m) in north-central New Mexico.

The Cowles Member (10 m) of the Tererro Formation indicates that sedimentation ceased in northern and central New Mexico in late Viséan (early Chesterian) time. In southwestern New Mexico, the Paradise Formation (134 m) represents shallow-marine sedimentation and ranges from Zone 15 (Meramecian) through Zone 19 (late Viséan and Namurian or end of Chesterian). The upper part of the Rancheria Formation (69 m) and the Helms Formation (50 m) of south-central New Mexico are a deeper water facies of the Paradise Formation.

Pennsylvanian sedimentary rocks in northern, central, and southern New Mexico truncate Mississippian sedimentary rocks of Namurian, Viséan, and Tournaisian age. The Pennsylvanian sequence is as much as 2,300 m thick in north-central New Mexico and is more than 600–900 m thick in the Delaware, Orogrande, and Pedregosa Basins areas. The most complete section is in the Big Hatchet Mountains, where a relatively continuous sequence is essentially conformable with underlying Chesterian strata and overlying Wolfcampian beds and contains Morrowan through Virgilian faunal equivalents.

Rocks of the Pennsylvanian System are present throughout New Mexico except where they were not deposited or where they have been removed by subsequent erosion. The major positive features during the Pennsylvanian were the Uncompahgre, Sierra Grande, Zuni, and Pedernal uplifts and the central-basin platform, a shallow-marine feature. Many of the sections consist of a lower clastic phase, a middle limestone unit, and an upper intertongued limestone and clastic-rock sequence, but facies change greatly from units on the margins of uplifts into dark carboniferous basinal sequences. These sequences indicate transgression of the sea in the Early Pennsylvanian, maximum inundations in the Middle Pennsylvanian and regression near the close of the period.

Age determinations are based mainly on fusulinid zones, but numerous other marine fossils are present. Pennsylvanian rocks have yielded significant quantities of oil and gas, contain some local coal lenses, are host rocks for base-metal and fluorite-barite-galena ores, and are quarried for road metal, flagstone, and material to make cement, brick, and tile.

MISSISSIPPIAN SYSTEM

PREVIOUS WORK

Fossils from Mississippian rocks of New Mexico (fig. 1) were first identified by White (1881) at Lake Valley, N. Mex. Cope (1882a, b) referred to the rocks at Lake Valley and proposed the name Lake Valley Formation.

Herrick (1904) used the name Kelly Limestone for the Mississippian rocks of the Magdalena

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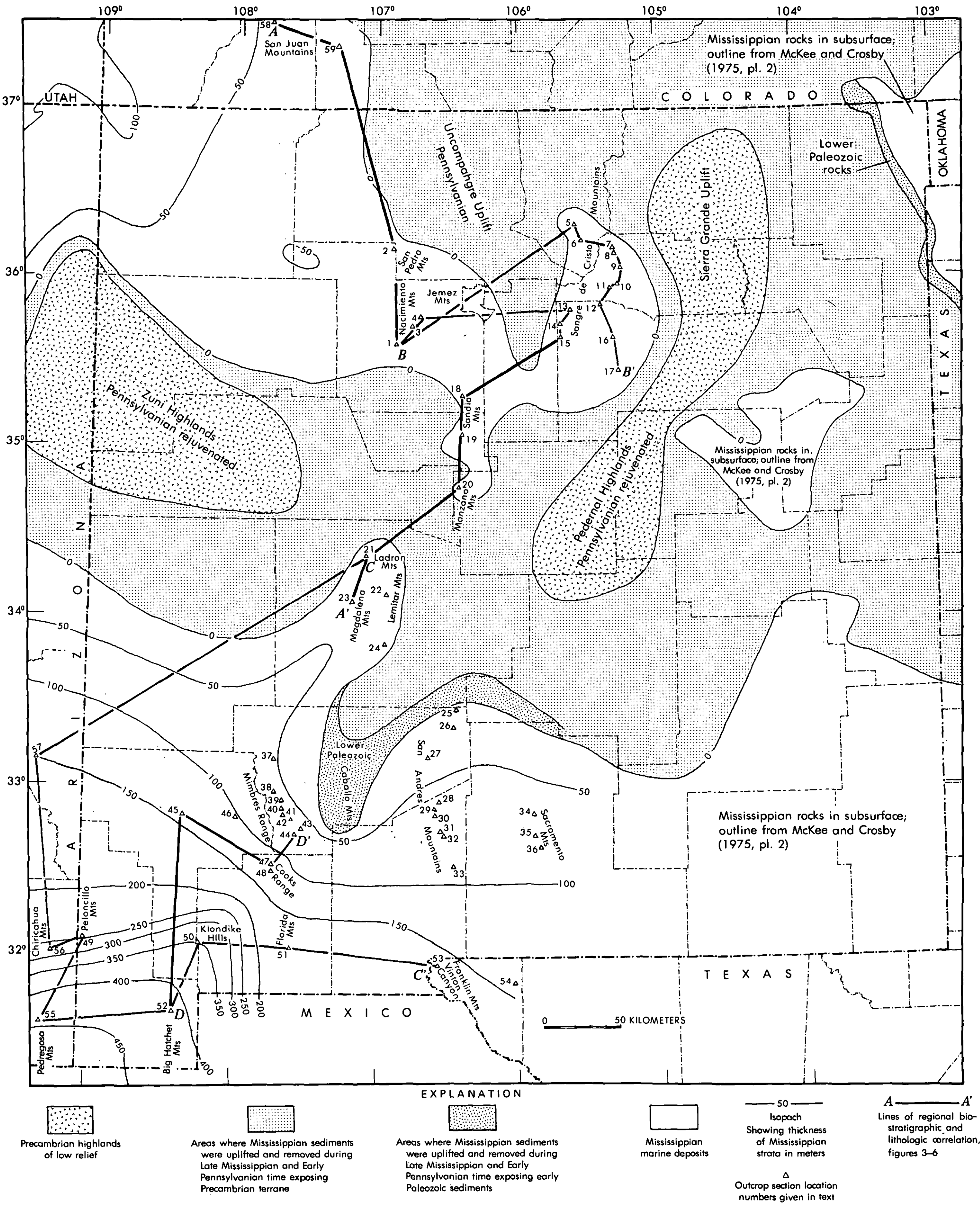


FIGURE 1.—Locations of Mississippian outcrop sections, pre-Pennsylvanian Mississippian isopachs and paleogeography, and locations of lines of biostratigraphic correlation charts (figs. 3–6) in New Mexico and nearby areas.

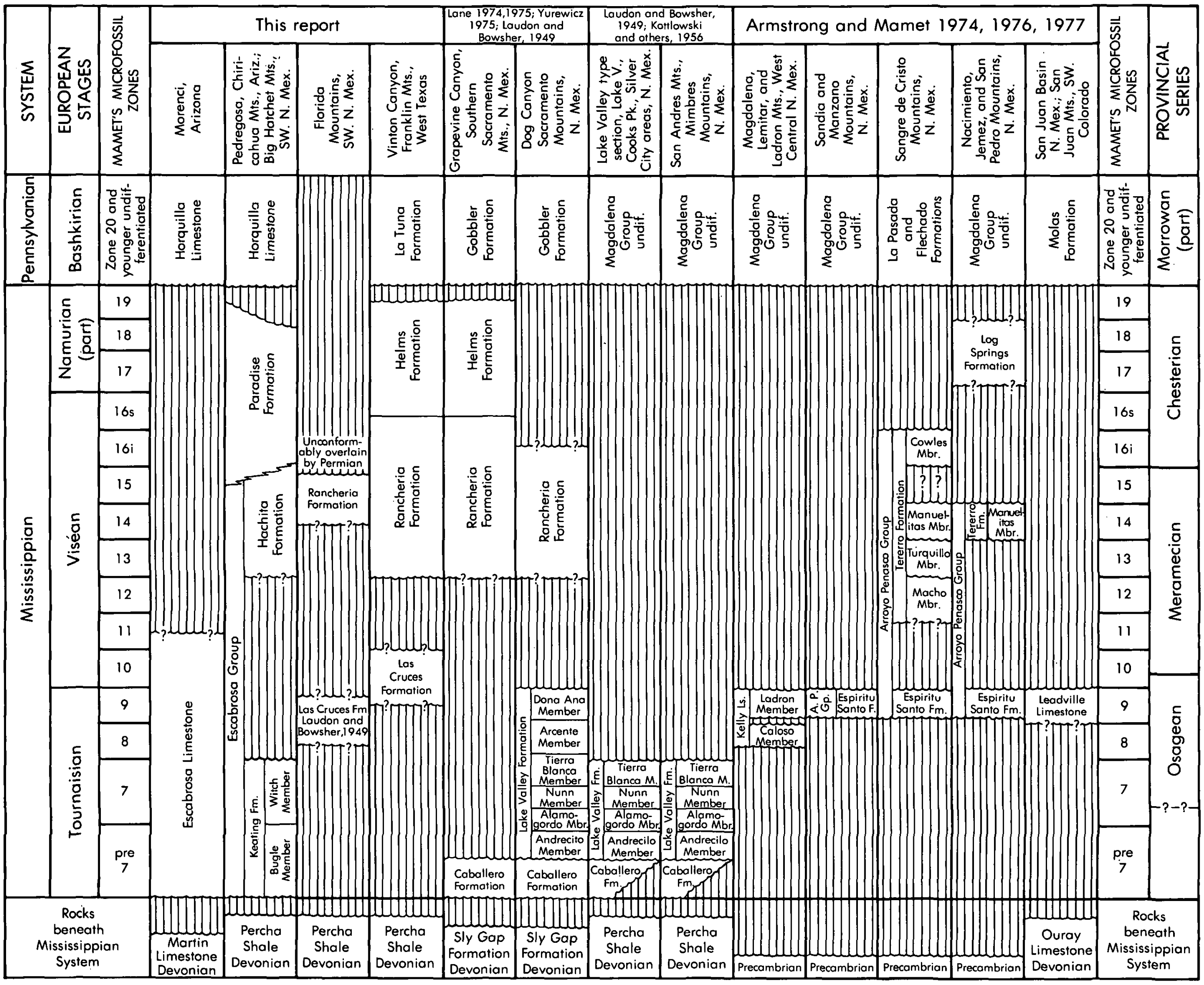


FIGURE 2.—Correlation chart of Mississippian rocks of New Mexico and nearby areas.

mining district. Laudon and Bowsher (1941, 1949) divided the Mississippian System and south-central New Mexico into five formations and divided the Lake Valley Formation into six members (fig. 2). They named the Caballero Formation for rocks of Kinderhookian age in the Sacramento and San Andres Mountains and at Lake Valley, N. Mex., and named the Las Cruces and Rancheria Formations for Meramecian rocks in the Franklin Mountains of western Texas and in the southern San Andres and Sacramento Mountains of New Mexico. They restricted Beede's (1920) designation of the Helms Formation to beds of Chesterian age. Laudon and Bowsher (1941, 1949) gave macrofaunal lists for the Lake Valley, the Rancheria, and the Helms Formation.

A section of pre-Pennsylvanian predominantly carbonate rocks of Paleozoic age in the San Pedro, Nacimiento, Jemez, Sandia, and Sangre de Cristo Mountains of northern New Mexico was studied by Read and others (1944), who first recognized the distinctiveness of these rocks. They mapped them as the lower limestone member of the Pennsylvanian Sandia Formation of the Magdalena Group. The lower gray limestone member was mapped and described by Wood and Northrop (1946) in the San Pedro and Nacimiento Mountains and by Northrop and others (1946) in the southeastern foothills of the Sangre de Cristo Mountains.

In 1955, Armstrong proposed the name Arroyo Penasco Formation for the lower gray limestone member of the Sandia Formation in the San Pedro, Nacimiento, Sandia, and Sangre de Cristo Mountains of north-central New Mexico.

Fitzsimmons, Armstrong, and Gordon (1956) listed a fauna of St. Louis (Meramecian) age that consisted of megafossils from the top of the Arroyo Penasco Formation in exposures on the northwestern side of the San Pedro Mountains and from its type section. Armstrong (1958a, 1967) described part of the Meramecian endothyrid fauna of the Arroyo Penasco Formation and demonstrated that at the type section and in the Sangre de Cristo Mountains, the rocks had the same lithologies and endothyrid species and were thus of the same age.

Because of the discovery of the *Spinoendothyra spinosa* (Chernysheva) microfauna in cherts of the basal carbonate rocks by Lee Holcomb of the Shell Oil Company, Armstrong (1963, p. 115; 1965, p. 133; 1967; Armstrong and Holcomb, 1967) determined the age of the Arroyo Penasco Formation to be late Osagean and Meramecian.

In 1960, Baltz and Read divided the pre-Pennsylvanian sandstone and carbonate rocks of the Sangre de Cristo Mountains into two newly named formations, the Espiritu Santo (Devonian(?)) and the Tererro (Kinderhookian to Meramecian). The Tererro Formation was divided into three members, in ascending order, the Macho, Manuelitas, and Cowles Members.

Armstrong (1967) considered Baltz and Read's (1960) Espiritu Santo and Tererro Formations of the Sangre de Cristo Mountains to be laterally equivalent parts of his (Armstrong, 1955) Arroyo Penasco. He recognized the Arroyo Penasco throughout northern New Mexico. Armstrong and Mamet (1974) raised the Arroyo Penasco to group rank. The age and nomenclature of these rocks are shown in figure 2.

The Escabrosa Limestone of Mississippian age was named by G. H. Girty (*in* Ransome, 1904) for the lower Carboniferous section in the Escabrosa Cliffs, west of Bisbee, Cochise County, southeastern Arizona. The Escabrosa Limestone in the Chiricahua Mountains of southeastern Arizona and southwestern New Mexico was elevated by Armstrong (1962, p. 5) to the Escabrosa Group, which he divided into two newly named formations—the Keating Formation, consisting of two members, A and B, and the overlying Hachita Formation (fig. 2). This nomenclature was extended into Luna, Hidalgo, and Grant Counties, southwestern New Mexico. The two informal members, A and B, of the Keating Formation were named the Bugle and Witch Members of the Keating Formation by Armstrong and Mamet (1978). The names are taken from the Bugle Ridge and Witch Well, published on the U.S. Geological Survey's 1:62,500 scale topographic map of the Big Hatchet Quadrangle. The type sections for the members are E½ sec. 30, T. 29 S., R. 15 W., northeast side of the Big Hatchet Mountains. Armstrong (1962) illustrated and described the brachiopod and coral faunas of the Escabrosa Group.

The Paradise Formation was named by Stoyanow (1926) for outcrops a few kilometers east of the old mining camp of Paradise, on the east side of the Chiricahua Mountains. The macrofauna of the Paradise Formation in the Chiricahua Mountains was studied and described by Hernon (1935). Zeller (1965) gave M. K. Elias' macrofossil lists of the Paradise Formation for the Big Hatchet Mountains outcrop.

The stratigraphic nomenclature used in this paper has not been reviewed by the Geologic Names Committee of the U.S. Geological Survey. The nomenclature used here conforms with the current usage of the New Mexico Bureau of Mines and Mineral Resources.

GEOLOGIC SETTING

LOWER BOUNDARY OF THE MISSISSIPPIAN

The Leadville Limestone of the San Juan Mountains, Colo., and in the subsurface of San Juan County, N. Mex., has at its base a Tournaisian (Osagean) microfossil assemblage of Zone 9 (Armstrong and Mamet, 1976, 1977), and the underlying Ouray Limestone contains a well-defined fauna of Late Devonian brachiopods near its top (figs. 2, 3). In north-central New Mexico, Mississippian rocks of Zone 9 age unconformably overlie Precambrian metamorphic and igneous rocks (figs. 2–4). In west-central New Mexico, Zone 8 rocks overlie Precambrian rocks. In the Sacramento Mountains, pre-Zone 7 rocks overlie shale and limestone of Late Devonian age. In the northern San Andres Mountains, Tournaisian-age rocks rest unconformably on Upper Devonian shale and marl; in the southern part of the range, pre-Zone 7 beds unconformably overlie the Upper Devonian rocks. In the Mimbres Range and Silver City region, pre-Zone 7 rocks unconformably overlie the Upper Devonian Percha Shale. In the southwestern part of the State, pre-Zone 7 carbonate rocks unconformably overlie the Upper Devonian Percha Shale (figs. 5, 6).

UNITS OVERLYING THE MISSISSIPPIAN

Pennsylvanian rocks unconformably overlie the Mississippian at most places in New Mexico. In the mountains of north-central New Mexico, the Mississippian Arroyo Penasco Group and the Log Springs Formation are overlain by Pennsylvanian sedimentary rocks. The Lower Pennsylvanian Molas Formation overlies the Leadville Limestone in the subsurface of San Juan County. The hiatus probably represents active erosion of Mississippian rocks during Zones 17 to 20 (Chesterian to Morrowan) time.

In west-central New Mexico in the Lemitar, Ladron, and Magdalena Mountains, the Mississippian carbonate rocks are unconformably overlain by nearshore clastic rocks of the Pennsylvanian Sandia Formation. In the Coyote Hills southwest of Socorro, Tertiary volcanic rocks overlie and truncate the Mississippian outcrops.

Pennsylvanian sedimentary rocks in northern, central, and southern New Mexico truncate Mississippian sedimentary rocks of Namurian, Viséan, and Tournaisian (Chesterian to Osagean) age. In the Big Hatchet Mountains, however, the contact between the Paradise Formation and the Horquillo Limestone is at the boundary between Zones 19 and 20, and a hiatus, if present, must be minimal. In the Florida Mountains, the Mississippian is unconformably overlain by Wolfcampian (Permian) carbonate rocks.

STRUCTURAL EVENTS DURING THE MISSISSIPPIAN

An idealized illustration of the total thickness of Mississippian rocks is shown in figure 1. The map shows disconnected areas of Mississippian rock remnants of extensive sheets that were dissected and beveled in northern and central New Mexico in Namurian (Chesterian) time and throughout the entire State by erosion on structurally active features in Pennsylvanian and Permian time.

Marine flooding of the State began in early Tournaisian (pre-Zone 7) time in the southwestern and south-central part of the State and formed the Escabrosa carbonate platform. By the end of Tournaisian (Osagean) time, epicontinental seas had flooded the northern and central parts of the State. Two possible low islands may have existed, the Zuni Highlands and remnants of the transcontinental arch, the Pedernal Highlands (fig. 1). The Espiritu Santo Formation (figs. 2–4) is composed of carbonate tidal deposits in the Sangre de Cristo, Sandia, Nacimiento, and San Pedro Mountains of north-central New Mexico (Armstrong, 1967; Armstrong and Mamet, 1977; Vaughan, Eby, and Meyers, 1977). The Leadville Limestone is the time-stratigraphic equivalent in the San Juan Basin of northwestern New Mexico and is an eastern extension of the Redwall Limestone of Arizona. The end of Tournaisian (Osagean) time was marked by a marine regression, a regional uplift, and extensive erosion of the Tournaisian (Osagean) carbonate deposits (figs. 2–6).

The geographic and stratigraphic extent of this hiatus at the end of the Tournaisian (Osagean) is shown in figures 2–6. A major regional marine transgression took place in middle Viséan (Meramecian) and is represented by the massive encrinites of the Hachita Formation in the southwestern part of the State, the deeper water carbonate rocks of the Rancheria Formation in the southern San Andres and Sacramento Mountains, and the Turquillo Member (Meramecian) of the Tererro Formation in north-central New Mexico. Late Viséan carbonate rocks of Zone 16i (Chesterian) are also widely distributed in disjunct outcrops. These are the Cowles Member of the Tererro Formation, the upper part of the Rancheria Formation, and the lower part of the Paradise Formation.

Marine sedimentation ceased in northern and central New Mexico at the end of Zone 16i time. In southwestern New Mexico, marine sedimentation continued through Zone 19 time. The Paradise Formation (figs. 2, 5, 6) is a series of shallow-water shoaling to nearshore oolitic carbonate rocks to plant-fossil-bearing crossbedded sandstones and siltstones. The Helms Formation to the east appears to be a deeper water facies equivalent of the Paradise Formation (figs. 2, 5).

The Log Springs Formation of the San Pedro, Nacimiento, Jemez, and Sandia Mountains of north-central New Mexico unconformably overlies the Arroyo Penasco Group and in turn is truncated by limestones of Pennsylvanian (Zone 20) age. The Log Springs Formation is composed of terrigenous, red-brown iron-rich shale, siltstone, and lithic to arkosic conglomerate formed of angular cobbles of Mississippian and Precambrian rocks. It is interpreted as being post-Zone 16i and pre-Zone 20 in age (Namurian (Chesterian)) and represents, in part, a regolith and tectonically derived sediments washed into small basins adjacent to uplifted, faulted, and tectonically active highlands (figs. 2–4).

The biostratigraphy and facies relations of the Mississippian carbonate rocks in the San Andres

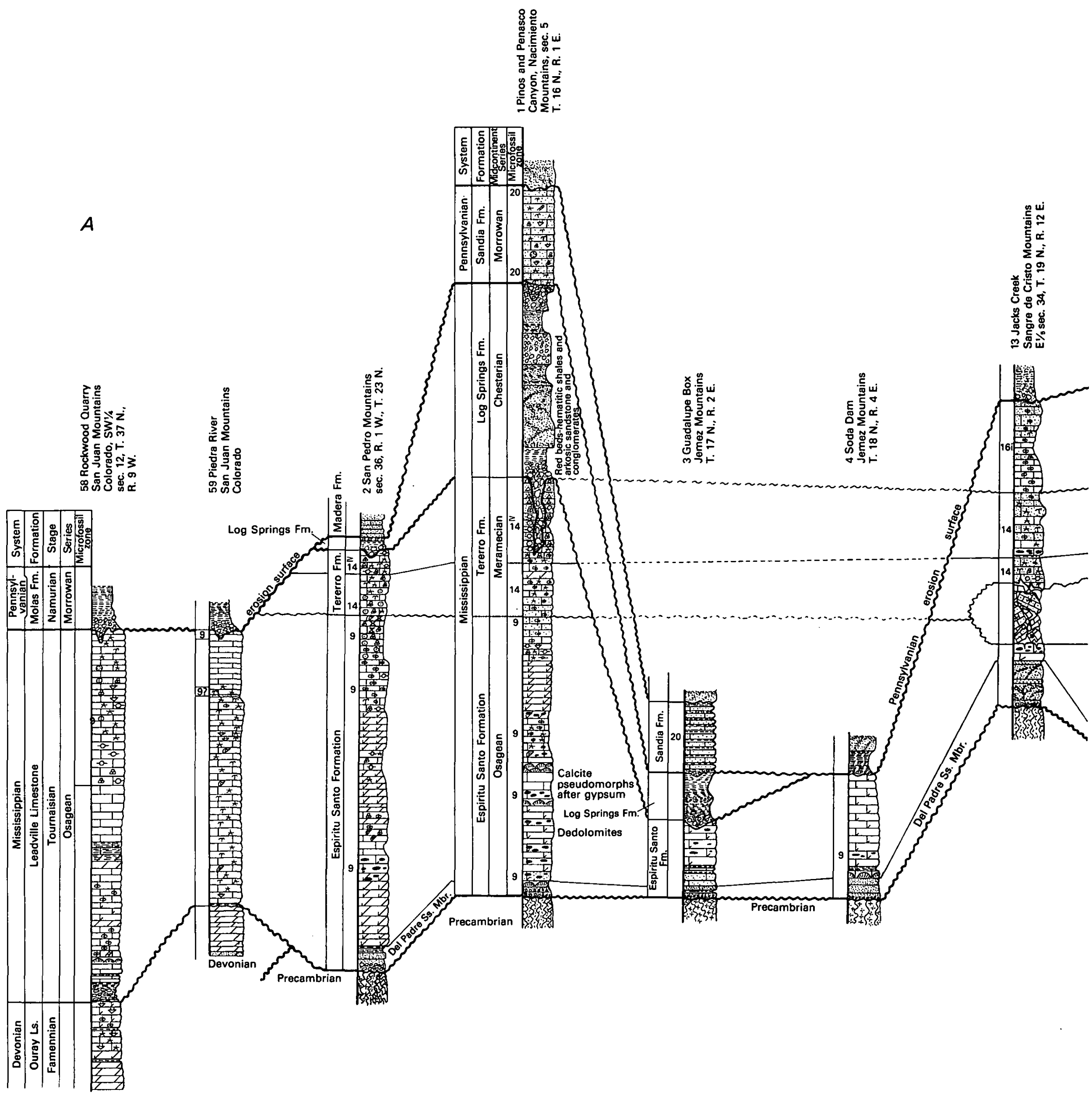


FIGURE 3.—Regional biostratigraphic and lithologic correlation of Mississippian strata along line *A–A′* from the San Juan Mountains of southwestern Colorado to the San Pedro, Nacimiento, Jemez, Sangre de Cristo, Sandia, Manzano, Ladron, and Magdalena Mountains of northern New Mexico. Line of section is shown in figure 1; symbols are explained in figure 5.

and Sacramento Mountains of south-central New Mexico are well described. The first modern studies of the Mississippian of the Sacramento and San Andres Mountains were by Laudon and Bowsher (1941, 1949) on the stratigraphy and megafaunas of the Mississippian Caballero and Lake Valley Formations and the bioherms of the Lake Valley. They described the wedge-on-wedge relations between these Lower Mississippian strata and the Upper Mississippian Rancheria and Helms Formations.

James Lee Wilson (1975, p. 125) stated the problem of the stratigraphic relationship of the Lake Valley Formation to the Rancheria and Helms Formations:

> The distribution of Mississippian beds in southern New Mexico is stratigraphically puzzling. Fine-grained and siliceous limestone and shale of the Late Mississippian Rancheria and Helms formations are apparently the only strata representing the system in the Franklin and Hueco Mountains around El Paso, whereas to the north and west in New Mexico thick crinoidal Osagean beds are present; only Early Mis-

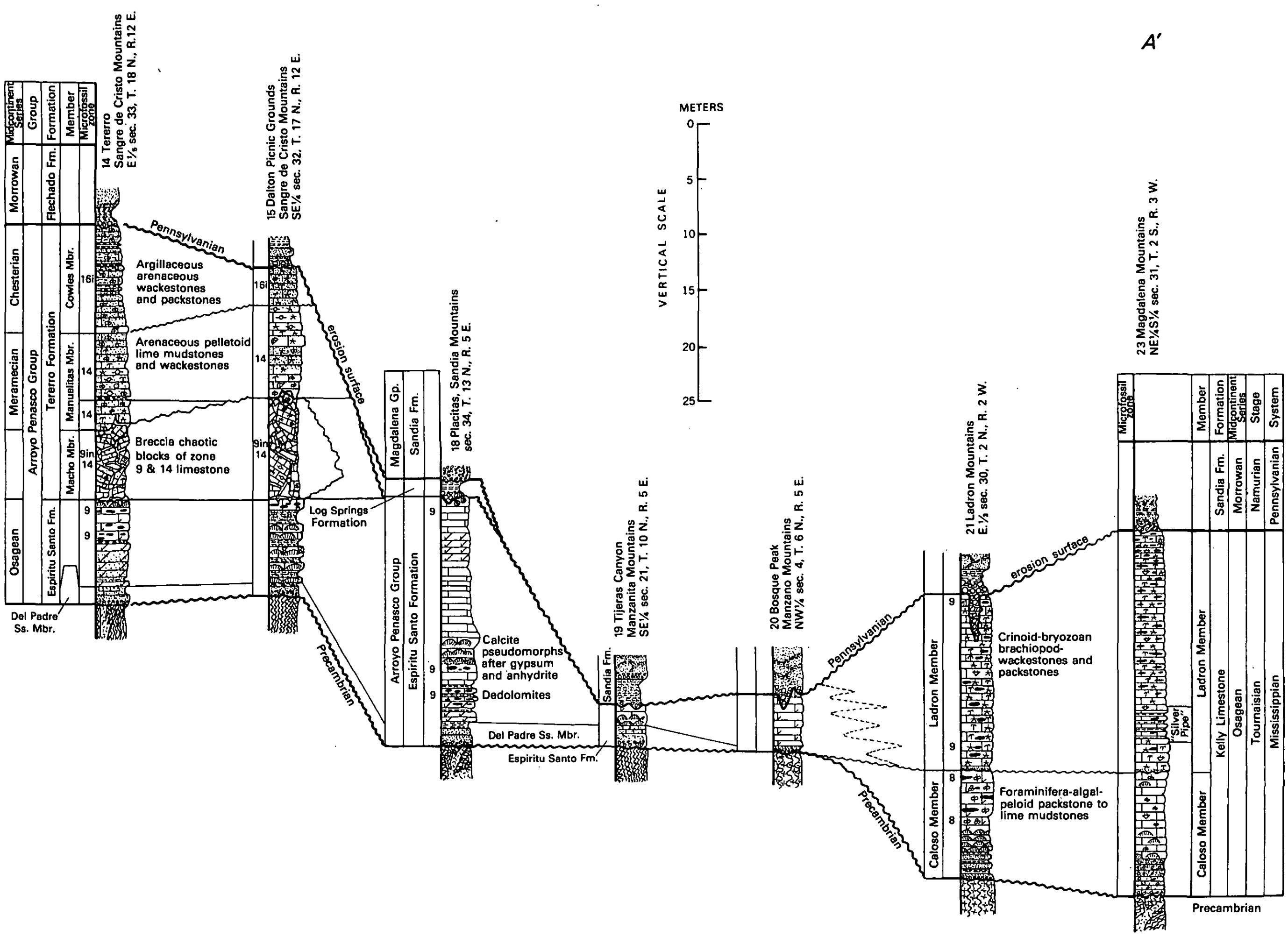


FIGURE 3.—Continued.

sissippian strata are known in the northern San Andres and Sacramento Mountains. Is this reciprocal distribution of major parts of the Mississippian best explained by differential tectonic uplift and erosion, or could it be in some way depositional in origin? Some data bearing on the problem are given below.

Regional Mississippian isopachs of southern New Mexico by A. K. Armstrong (1962) and F. E. Kottlowski (1970) indicate a considerable thickness (500 meters) of mostly Early Mississippian shelf encrinite in the southwestern part of the state and in adjacent Arizona. Control points for this occur in the Big Hatchet Mountains, Sierra de Palomas, and the Los Chinos oil test of Petroleos Mexicanos. These thick open marine shelf deposits grade eastward into thinner and more micritic limestone with some shale and with large scattered bioherms as displayed by the Sacramento Mountain outcrops. Pray (1961) and Meyers (1973) have demonstrated that the Sacramento Mountain strata represent deposition down a gentle southward slope. Correlation of detailed stratigraphic profiles along the north-south trending Sacramento scarp shows this clearly. Well-bedded shelf encrinites, with lens-shaped Waulsortian micritic bodies change southward to larger, equidimensional Waulsortian mud mounds surrounded by encrinites and dark micritic limestones. The strata thin unit by unit and together form a wedge tapering out in the Franklin and Hueco Mountains (Lane, 1974). The absence of Osagean Mississippian in the El Paso area and the presence there of only fine-grained and siliceous Meramecan [sic] and Chesteran strata were first pointed out by Laudon and Bowsher (1949). Late Mississippian strata wedge out northward, the uppermost Rancheria and Helms being present only in the southern Sacramento Mountains. Was an originally widespread sheet of Osagean limestone eroded from this southern area along a trend cutting transverse to the later Paleozoic structural grain, across both the Diablo platform and the Pedregosa basin? Or was the later Paleozoic depositional topography already set in Mississippian time? Could there have been an extended Oro Grande-Pedregosa basin in New Mexico and Chihuahua which was starved of sediment during Kinderhookian and Osagean time and filled with the basinal Rancheria during Meramecan [sic]? Armstrong (1962), the writer (Wilson, 1969, 1971 [1970]), and Kottlowski (1970) have all suggested the latter interpretation. The following lines of evidence indicate that this is

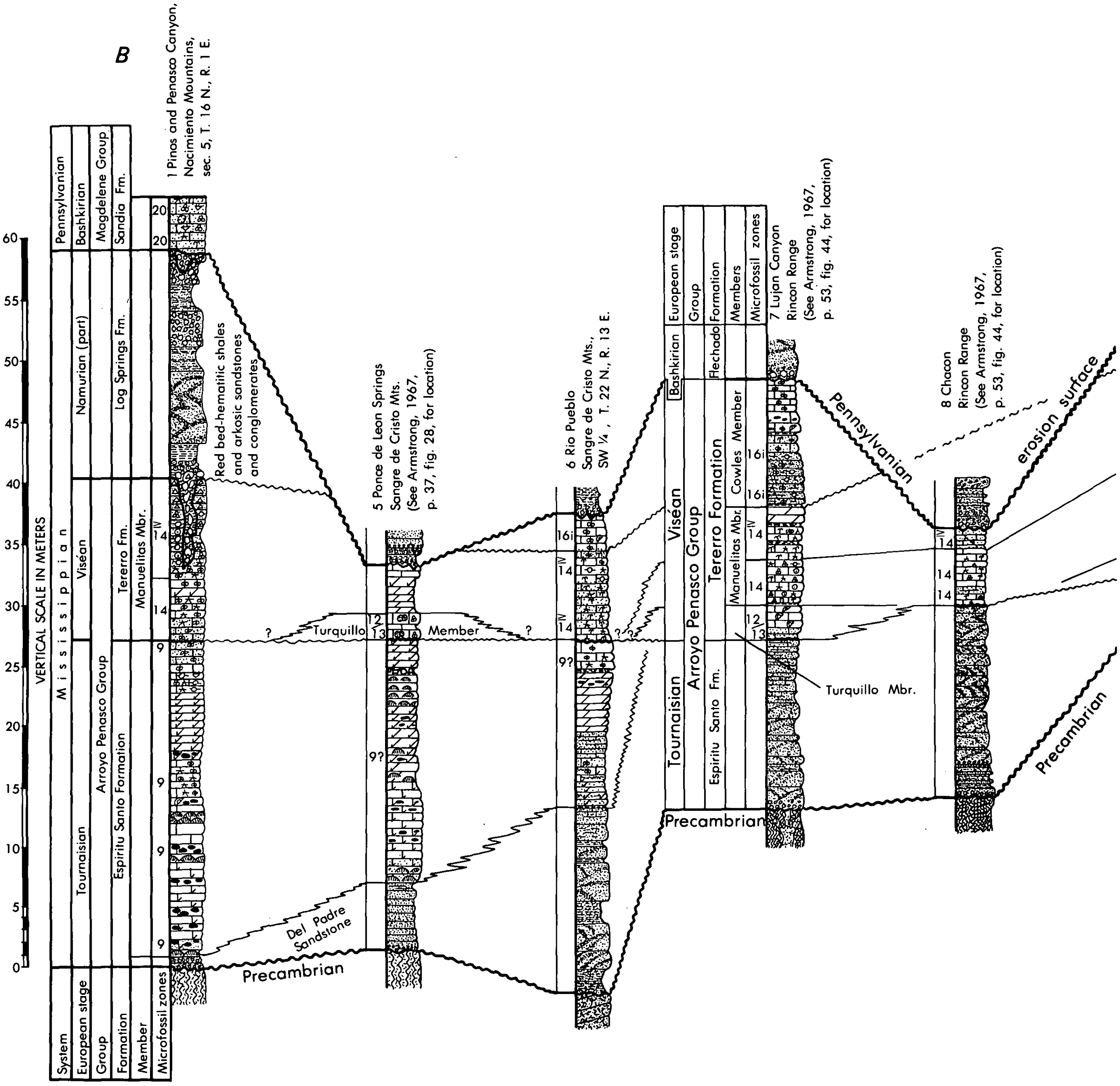


FIGURE 4.—Regional biostratigraphic and lithologic correlation of Mississippian strata along line *B–B′* from the Nacimiento and Sangre de Cristo Mountains of north-central New Mexico. Line of section is shown in figure 1; symbols are explained in figure 5.

reasonable but do not offer compelling proof. No paleontologic evidence of Early Mississippian beneath the Rancheria has yet been presented.

The facies of the southward tapering and prograding wedge of Early Mississippian strata in the Sacramento Mountains are best explained by deposition on a gentle slope south into a starved basin; e.g. the Waulsortian bioherms get larger and more equidimensional to the south before they disappear.

W. J. Meyers' (1974, 1975) reports on the Mississippian stratigraphy and diagenesis are based on petrographic and cathodo-luminescence studies of the carbonate sediments, cementation, and chert. He demonstrated that the nonferroan calcite cement zones in the Lake Valley Formation reflect ancient phreatic lenses established during pre-Viséan (pre-Meramecian) and pre-Bashkirian (pre-Morrowan) periods, when meteoric waters cemented these rocks below unconformities.

D. A. Yurewicz' (1975) investigation of the basin-margin sedimentary rocks of the Viséan and Namurian (Meramecian) Rancheria Formation in

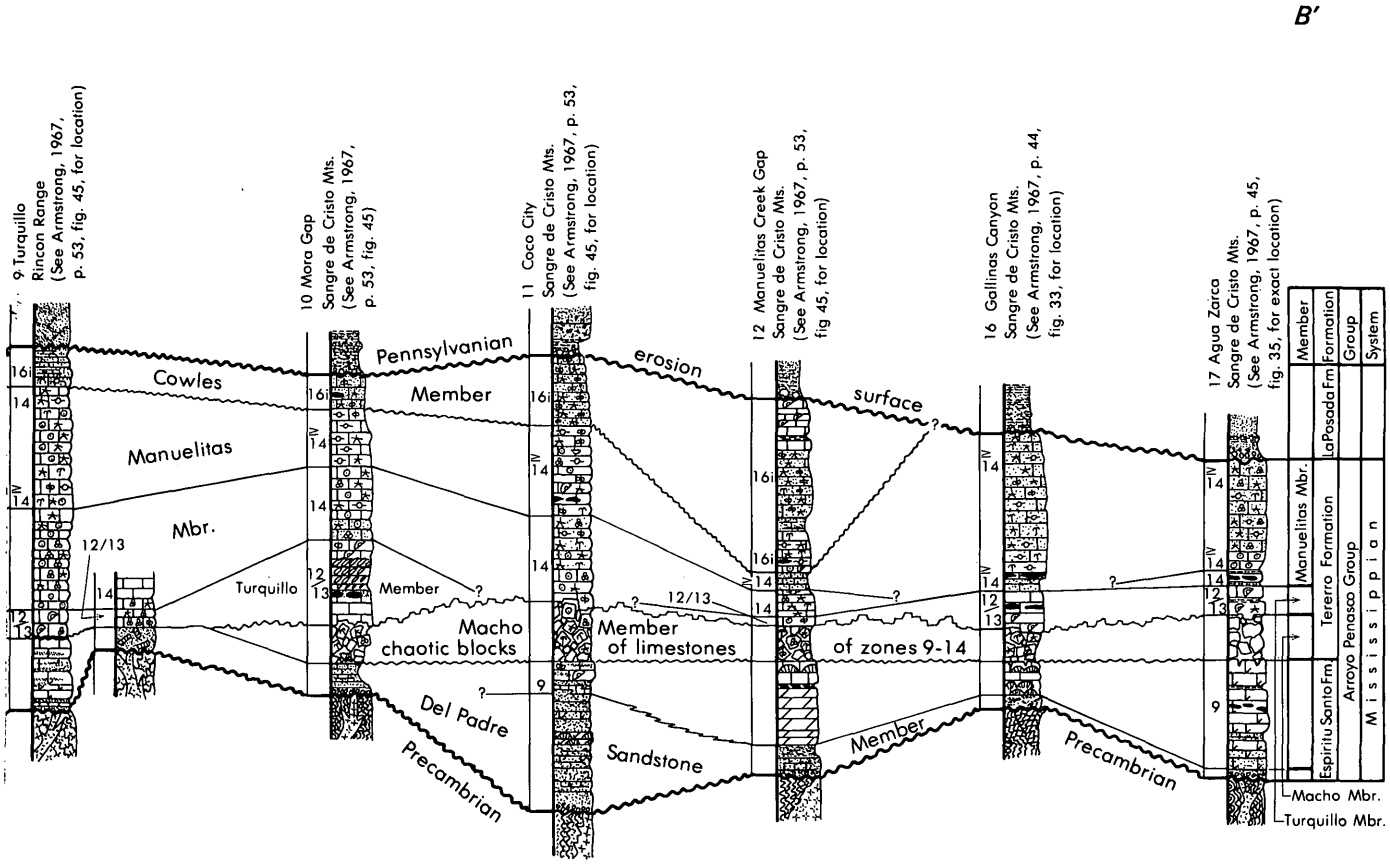


FIGURE 4.—Continued.

the Sacramento Mountains shows that the Rancheria Formation is younger than the Lake Valley Formation (Tournaisian (Osagean)) and is separated from it by an unconformity.

H. Richard Lane's (1974, fig. 4; 1975, fig. 3) study of the conodont faunas of the Lake Valley, Rancheria, and Helms Formations conclusively demonstrates that the Viséan and Namurian Rancheria Formation of the Franklin Mountains of east Texas and the southern San Andres and Sacramento Mountains of New Mexico has a wedge-on-wedge relation with the Tournaisian (Osagean) shelf carbonate rocks and bioherms of the Lake Valley Formation; the Rancheria and Lake Valley wedges are separated by an unconformity. The Viséan and Namurian (Zones 14–19, Meramecian–Chesterian) Rancheria and Helms Formations of western Texas and the Florida Mountains, N. Mex., also have a wedge-on-wedge relation with the Tournaisian Keating Formation of southwestern New Mexico (fig. 5) and are separated from the Keating by an unconformity.

LOCATIONS OF MISSISSIPPIAN OUTCROPS

Locations of Mississippian outcrop sections used in this report are shown on figure 1 and are described in the publications listed as follows, by section numbers:

1–20. Armstrong (1967), Armstrong and Mamet (1974), Baltz and Read (1960); The areas are the San Pedro, Nacimiento, Sangre de Cristo, Sandia, Manzano, and Jemez Mountains, N. Mex.

21–24. Armstrong (1958b); Ladron, Magdalena, Lemitar Mountains, and Coyote Hills, N. Mex.

25–33. Laudon and Bowsher (1949), Kottlowski and others (1956), Kottlowski (1975b); San Andres Mountains, N. Mex.

34–36. Laudon and Bowsher (1941, 1949), Pray (1958, 1961), Meyers (1973, 1974, 1975), Lane (1974, 1975), Yurewicz (1973, 1975); Sacramento Mountains, N. Mex.

37–48. Laudon and Bowsher (1949); Mimbres and Cooks Ranges, Silver City area, New Mexico.

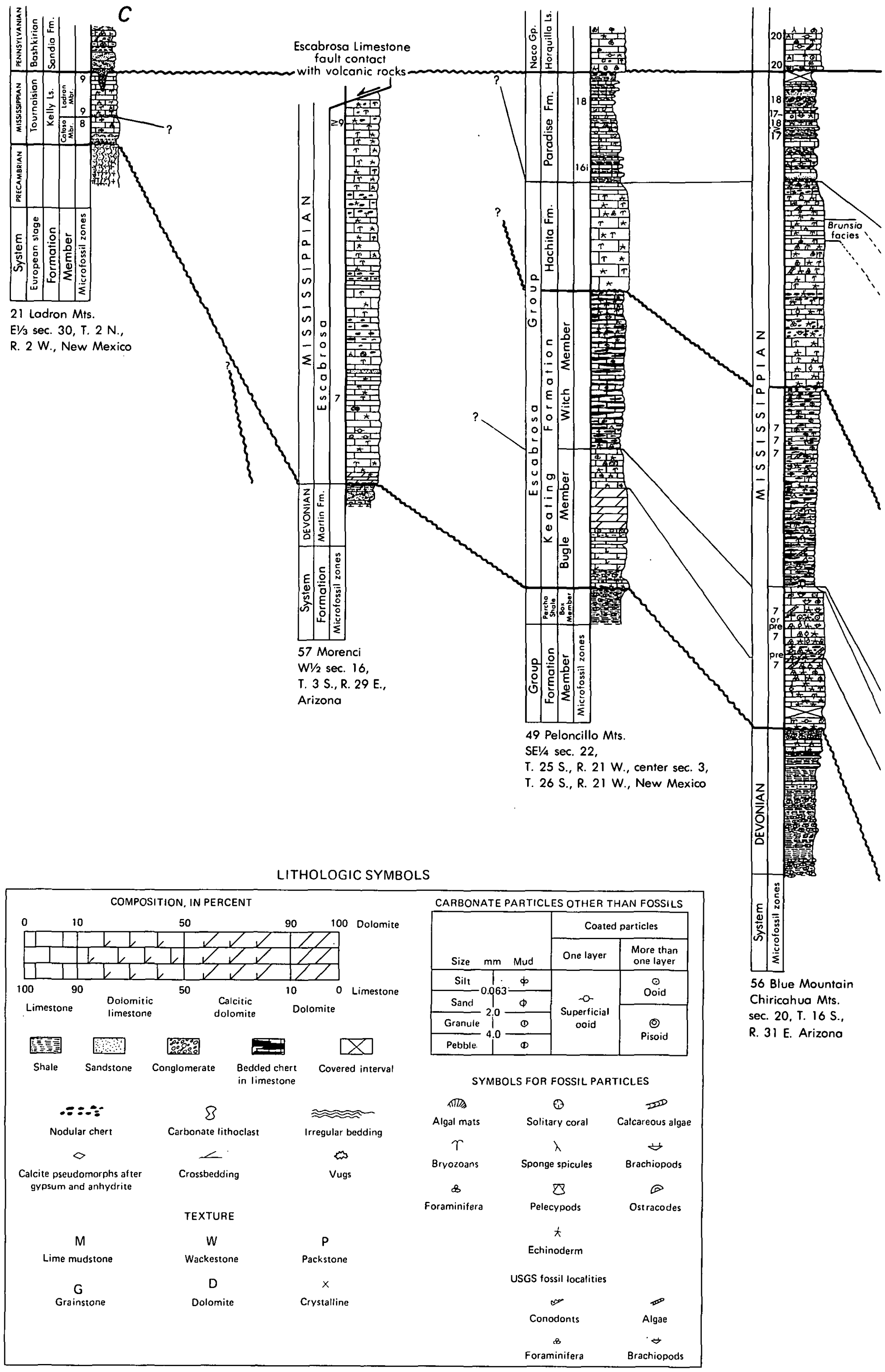
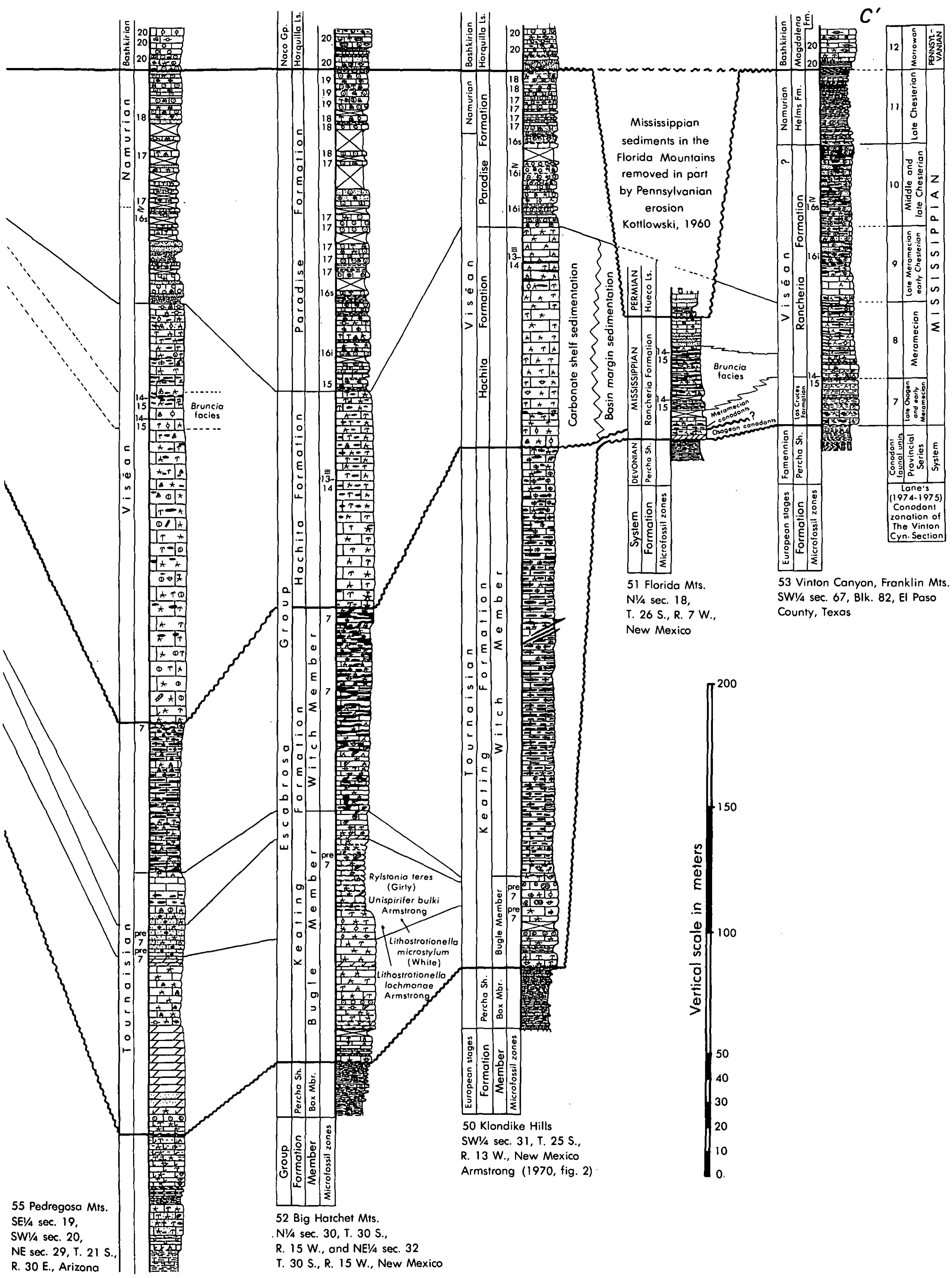


FIGURE 5.—Regional biostratigraphic and lithologic correlation for Mississippian strata along tains, southeastern Arizona, the Peloncillo Mountains, New Mexico, the Pedregosa Moun- ern New Mexico, to the Franklin Mountains and Vinton Canyon, western Texas. Line of



line *C–C′* from the Ladron Mountains, west-central New Mexico, to Clifton, Arizona, the Chiricahua Mountains, southeastern Arizona, the Big Hatchet Mountains, Klondike Hills, and Florida Mountains, southwest-section is shown in figure 1.

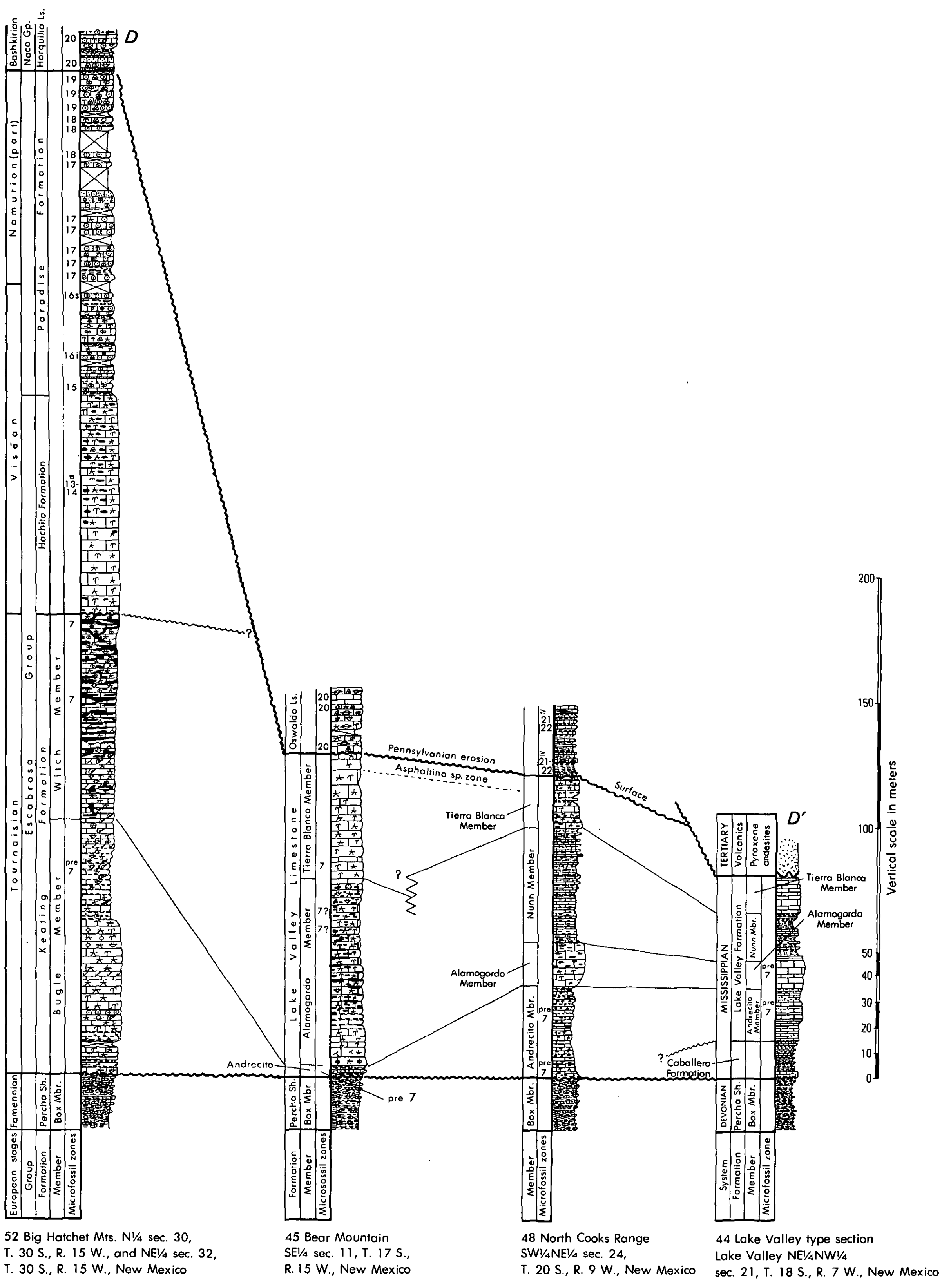


FIGURE 6.—Regional biostratigraphic and lithologic correlation of Mississippian strata along line *D–D'* from the Big Hatchet Mountains to Bear Mountain and the Mimbres Range, southwestern New Mexico. Line of section is shown in figure 1; symbols are explained in figure 5.

49–52. Armstrong (1962, 1970); Peloncillo, Big Hatchet, and Florida Mountains, Klondike Hills, N. Mex.

53, 54. Laudon and Bowsher (1949), Lane (1974, 1975); Vinton Canyon, Franklin Mountains, and Hueco Mountains, west Texas.

55. Epis (1956); Pedregosa Mountains, Ariz.

56. Sabins (1957); Chiricahua Mountains, Ariz.

57. Lindgren (1905); Clifton-Morenci district, Arizona.

58, 59. Armstrong and Mamet (1976); San Juan Mountains, Colo.

PENNSYLVANIAN SYSTEM

Pennsylvanian rocks in New Mexico represent a complete section in several areas, particularly in the southwestern and southeastern parts of the State, where a continuous section contains Morrowan to Virgilian equivalents. Rocks of this system are present throughout the State, except where they have been removed by erosion since the Pennsylvanian or where they were not deposited on the Pennsylvanian-age uplifts or preexisting highs. These major uplifts (fig. 7) were the Uncompahgre Uplift, in the north-central part of the State; the Sierra Grande, in the northeastern area; the Pedernal Uplift, extending through the central part of the State; the Zuni Uplift, in the west-central area; the Matador Arch, in the east-central area; and the Florida Uplift, in the southwestern part of the State.

The major outcrops of Pennsylvanian rocks are (1) in the Sangre de Cristo Mountains and Nacimiento Mountains, in the north-central part of the State; (2) in the Sandia, Manzano, Ladron, and Los Pinos Mountains and Lucero Mesa area, in central New Mexico; (3) in the Oscura, San Andres, Sacramento, Caballo, Fra Cristobol, and Robledo Mountains, of south-central New Mexico; and (4) in the Black Range, on Cookes Peak and Lone Mountain, in Silver City, and in the Peloncillo, Animas, and Big Hatchet Mountains, of southwestern New Mexico. The outcrops in southwestern New Mexico are in basin-and-range fault blocks.

Thick subsurface sections of Pennsylvanian rocks are present in the San Juan Basin of northwestern New Mexico, in many graben valleys of the southwestern and south-central part of the State, and in the subsurface of the western part of the Permian Basin in southeastern New Mexico and western Texas in the areas of the Delaware Basin and the northwest shelf. Sections of Pennsylvanian rocks are thickest (1) in the Sangre de Cristo Mountains, where they probably exceed 2,300 m in thickness (Baltz, 1972; Read and Wood, 1947; Sutherland, 1963), (2) in the Big Hatchet Mountains area of southwestern New Mexico and in the flanking Pedregosa Basin, where thicknesses are greater than 750 m, (3) in the Orogrande Basin of south-central New Mexico, where they are thicker than 900 m, and (4) in the Delaware Basin of southeastern New Mexico and western Texas, where more than 600 m of Pennsylvanian rocks are present.

Uplifting of mountain ranges in Cenozoic time, particularly those bordering the Rio Grande rift and those in the basin-and-range country of south-central and southwestern New Mexico, resulted in exposure of many spectacular sections of Pennsylvanian rocks, particularly in the Sangre de Cristo, Sandia-Manzano, San Andres, Sacramento, Caballo, and Big Hatchet Mountains. Owing to the semiarid climate of the southern part of the State, Pennsylvanian limestones are well preserved in prominent peaks such as the Big Hatchet Mountains in southwestern New Mexico and the Oscura, Caballo, and San Andres Mountains of the south-central region.

HISTORY

Jules Marcou (1856), J. S. Newberry (1876), and others recognized Carboniferous rocks in early reconnaissance surveys. Stratigraphic sections and lists of Carboniferous fossils from the north-central areas were published by J. J. Stevenson (1881). Keyes (1906) summarized the Carboniferous sections in south-central areas. Gordon (1907) named the Magdalena Formation from outcrops in the Magdalena Mountains, and Lee (1909) and Darton (1928) briefly described Pennsylvanian rocks in various areas of New Mexico. The Carboniferous rocks in the Silver City mining area were described by Paige (1916) and Spencer and Paige (1935). Many of the early descriptions of Carboniferous rocks were from the mining districts in the southwestern, central, and north-central parts of the State.

Exploration for oil and gas, spurred by World War II, led to many reports in the 1940's and essentially began modern studies of the Pennsylvanian in the State (table 1). Expansion of the work by the New Mexico Bureau of Mines and Mineral Resources and by the U.S. Geological Survey and many projects by university professors and their students, many of them supported by the New Mexico Bureau of Mines and Mineral Resources, led to a rapid

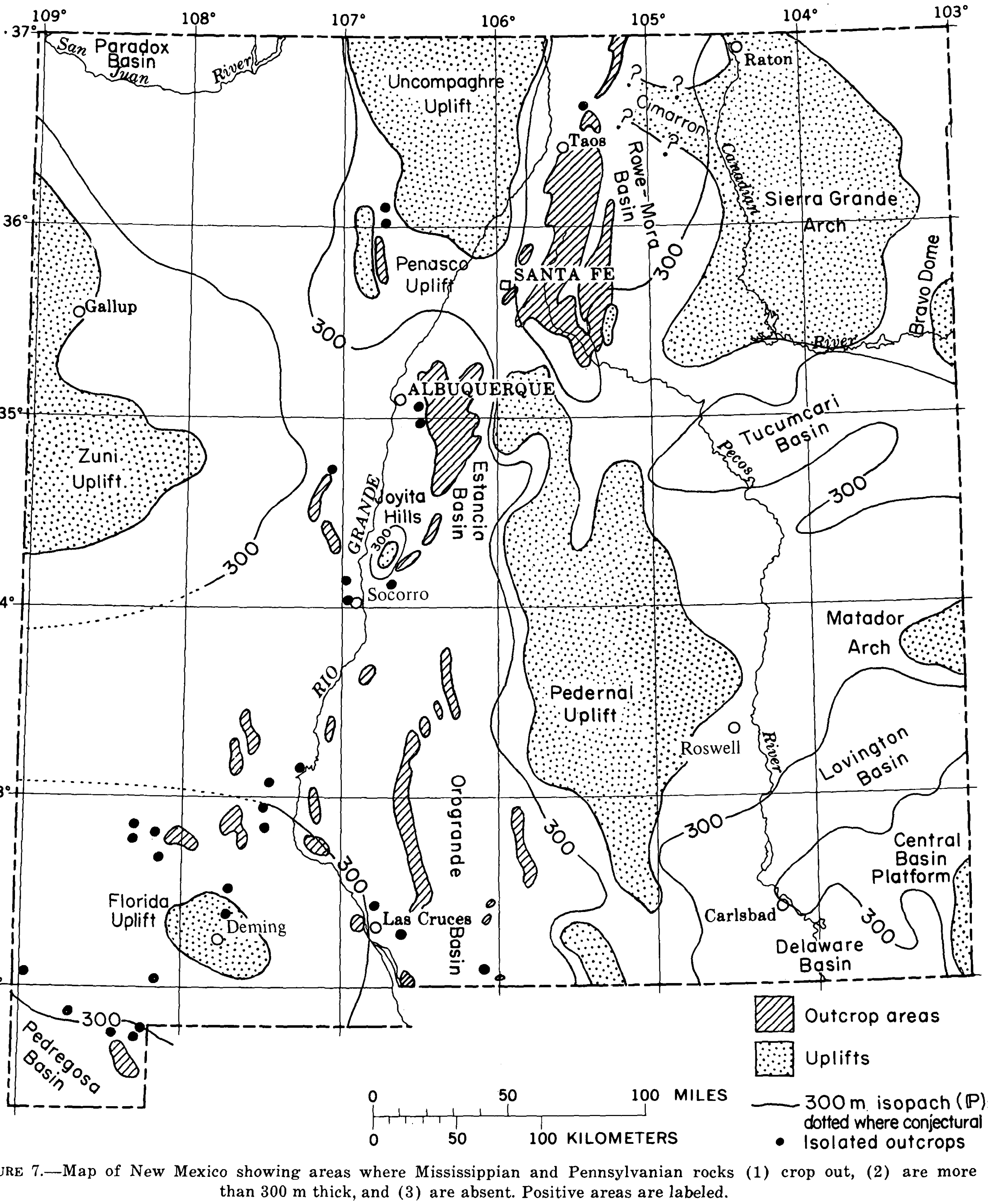


FIGURE 7.—Map of New Mexico showing areas where Mississippian and Pennsylvanian rocks (1) crop out, (2) are more than 300 m thick, and (3) are absent. Positive areas are labeled.

TABLE 1.—*Reports on the Pennsylvanian deposits of New Mexico, 1937–1978*

Year	Author(s)	Area or subject
	1930's	
1937	Needham	Fusulinids.
	1940's	
1940	Needham	Fusulinids.
1942	Thompson	Statewide.
1942	Loughlin and Koschmann.	Type Magdalena Formation.
1944	Henbest and Read	Sierra Nacimiento.
1944	Read	North-central New Mexico.
1946	Northrop	Southeastern Sangre de Cristo Mountains.
1946	Henbest	Central New Mexico.
1946	Wilpolt, MacAlpine, Bates, and Vorbe.	Do.
1946	Kelley and Wood	Lucero uplift.
1946	Stark and Dapples	Los Pinos Mountains.
1947	Read and Wood	Northern New Mexico.
1948	Thompson	Southern New Mexico.
1949	Lloyd	Southeastern New Mexico.
	1950's	
1950	Bradish and Mills	San Juan Basin.
1951	Wilpolt and Wanek	Central New Mexico.
1952	Brill	North-central New Mexico.
1952	Borden	San Juan basin.
1952	Kelley and Silver	Caballo Mountains.
1953	Kottlowski	Central New Mexico.
1953	Bachman	Mora County.
1953	Plumley and Graves	Virgilian reefs.
1954	Pray	Sacramento Mountains.
1954	Kuellmer	Black Range.
1955	Thompson and Kottlowski.	South-central New Mexico.
1956	Baltz and Bachman	Southeastern Sangre de Cristo Mountains.
1956	Kottlowski, Flower, Thompson, and Foster.	San Andres Mountains.
1957	Herman and Barkell	Paradox basin.
1958	Wengerd and Matheny.	Four Corners region.
1958	Kottlowski	Southwestern New Mexico.
1958	Galley	Southeastern New Mexico.
1958	Hardie	Northern Hueco Mountains.
1958	Gillerman	Peloncillo Mountains.
1958	Gehrig	Brachiopods.
1958	Bachman and Hayes	Sacramento Mountains.
1959	Cline	Do.
1959	Kottlowski	West-central New Mexico.
1959	Oppel	Sacramento Mountains.
1959	Otte	Do.
1959	Wengerd	Northwestern New Mexico.
	1960's	
1960	Kottlowski	Southwestern New Mexico.
1961	Pray	Sacramento Mountains.
1961	Northrop	Paleontology.
1961	Kottlowski	North-central New Mexico.
1962	Adams	Eastern New Mexico.
1962	Wray	Algal banks.
1962	Kottlowski	Southwestern New Mexico.
1962	Wengerd	Northwestern New Mexico.
1963	Sutherland	South Sangre de Cristo Mountains.
1963a	Kottlowski	South-central New Mexico.
1963b	Kottlowski	Socorro County.
1963c	Kottlowski	Sante Fe area.
1965	Baltz	Raton Basin.
1965	Kottlowski	Southwestern New Mexico.
1965	Zeller	Big Hatchet Mountains.
1966	Meyer	Southeastern New Mexico.
1967	Sutherland and Harlow.	Brachiopods.
1967	Wilson	Sacramento Mountains.
1969	Kottlowski	South-central New Mexico.
1969	Wilson	Southwestern New Mexico.
1969	Wilson, Madrid-Soils, and Malpica-Cruz.	Do.
	1970's	
1970	Kottlowski and Stewart.	Joyita area; fusulinids.
1971	Martin	Lucero Mesa.
1972	Baltz	Gallinas Creek area.
1972	Clark and Read	Eagle Nest area.
1972	Foster, Frentress, and Riese.	East-central New Mexico.
1972	Harbour	Franklin Mountains.
1972	Hills	Southeastern New Mexico.
1972	Wilson	Sacramento Mountains.
1972	Sutherland	Sangre de Cristo Mountains.
1973	King	Fusulinids.
1973	Myers	Manzano Mountains.
1973	Siemers	Socorro County.
1974	DuChene	North-central New Mexico.
1974	LeMone, King, and Cunningham.	Silver City Range.
1974	Northrop	Paleontology.
1975	Bachman	Entire State.
1975	Bachman and Myers	South-central New Mexico.
1975a, b	Kottlowski	San Andres Mountains.
1975	Thompson and Bieberman.	Doña Ana County.
1975	Zidek	Fossil fish.

TABLE 1.—*Reports on the Pennsylvanian deposits of New Mexico, 1937–1978*—Continued

Year	Author(s)	Area or subject
	1970's	
1976	Roberts, Barnes, and Wacker.	Northeastern New Mexico.
1977	Greenwood, Kottlowski, and Thompson.	Pedregosa Basin.
1978	Siemers	West-central New Mexico.

increase in the number of reports in the 1950's and 1960's (table 1). In the 1970's some notable regional papers and many detailed geologic maps showing areas of Pennsylvanian outcrops have been published. Some of these are listed in table 1.

The early regional papers were by Stevenson (1881), Gordon (1907), Lee (1909), and Darton (1928). More recent regional reports were those of Meyer (1966) and Galley (1958) on southeastern New Mexico, Wengerd (1962) on the San Juan basin area, Kottlowski (1960, 1962) on south-central and southwestern New Mexico, Read and Wood (1947) on north-central New Mexico, Baltz (1965) on the Raton Basin area, and Bachman (1975) as a summary of the Pennsylvanian in the State.

GEOLOGIC SETTING

UNDERLYING ROCKS

Mississippian rocks immediately underlie Pennsylvanian strata throughout New Mexico except along the flanks and on the crest of uplifts present in Pennsylvanian time. Along the flanks of the uplifts, particularly in south-central New Mexico, Pennsylvanian rocks lap northward onto Devonian, Silurian, Ordovician, or Cambrian units. The system rests on Precambrian rocks on the Sierra Grande Arch, Uncompahgre Uplift, Peñasco Uplift, Zuni Uplift, Joyita Hills, Pedernal Uplift, Florida Uplift area, Central Basin Platform, Matador Arch, and Bravo Dome.

NATURE OF CONTACT WITH UNDERLYING ROCKS

In many parts of southern New Mexico, oldest Pennsylvanian (Morrowan) rocks rest upon youngest Mississippian (Chesterian), and no hiatus is evident, although an erosion surface of low relief is seen locally. In the central and northern regions, the Morrowan laps out so that Atokan strata rest unconformably on older rocks. Moreover, the Chesterian is absent, adding to the missing section.

The erosional unconformity is evidenced by local channeling and slight reworking of Mississippian residual chert fragments into the lowest clastic strata of the Pennsylvanian. In some areas, such as the San Andres Mountains, Pennsylvanian beds were deposited on a pronounced erosional surface; in places, this surface cuts through the entire Mississippian section and the basal channel fills of the Pennsylvanian are chiefly chert-pebble conglomerates. In most areas where detailed mapping has been done, the basal clastic phase of the Pennsylvanian varies greatly in thickness from place to place and is almost entirely absent above low-relief hills of pre-Pennsylvanian rocks.

OVERLYING ROCKS

Pennsylvanian rocks are overlain by Permian (Wolfcampian) strata throughout the State except along the crest of some of the Laramide and Cenozoic uplifts where post-Paleozoic erosion has stripped off the overlying Permian deposits, and Tertiary volcanic rocks rest unconformably on the Pennsylvanian.

NATURE OF CONTACT WITH OVERLYING ROCKS

The Pennsylvanian-Permian contact in many areas appears to be conformable. In these areas, the boundary is somewhat arbitrarily drawn within a few tens of meters between the highest Virgilian and the lowest Wolfcampian fossil control. Permian rocks at some localities, as well as Cretaceous and Tertiary rocks in other places, are erosionally unconformable on the Pennsylvanian strata.

Along the edges of the uplifts that persisted into Permian time, such as the Pedernal and Uncompahgre Uplifts, Pennsylvanian beds were overlapped by Permian strata or were removed by erosion prior to Permian deposition. Upper Pennsylvanian rocks probably never were deposited on the crests of these uplifts. Pennsylvanian rocks may never have been deposited in parts of the Florida Uplift in southwestern New Mexico. Erosion during early and middle Mesozoic time stripped pre-Mesozoic rocks from the crest of the Burro Uplift in that area; on the northeast flank, Cretaceous beds rest with erosional unconformity on Pennsylvanian strata. Likewise, during the Laramide deformation in southwestern New Mexico, erosion stripped the crests of the highs so that Tertiary volcanic rocks rest unconformably on upper Paleozoic rocks in some localities.

In the north-central part of the State in the Sangre de Cristo Mountains area, Pennsylvanian rocks are overlain by the Sangre de Cristo Formation of Late Pennsylvanian and early Wolfcampian age. The nature of the contact is problematic at places because nonmarine arkoses and red beds of the Sangre de Cristo Formation transgress the time boundary and intertongue with the underlying fossiliferous Upper Pennsylvanian mixed-marine-nonmarine sedimentary rocks. Throughout most of the northern half of New Mexico, the Wolfcampian Abo red beds or time-equivalent continental facies overlie Pennsylvanian strata. In some central areas, a gradational sequence of interbedded limestones and red beds at the base of the Permian rests conformably on Virgilian rocks. In south-central and southeastern New Mexico, marine shelf carbonate rocks of the Hueco Formation overlie Pennsylvanian rocks conformably and in some places with an abrupt unconformity, as in the Hueco Mountains area. In southwestern New Mexico in the Big Hatchet Mountains area, the systemic boundary is within the upper part of the thick Horquilla Formation, a monotonous marine limestone sequence containing some shale.

STRUCTURAL EVENTS DURING PENNSYLVANIAN TIME

Positive and negative elements active in pre-Pennsylvanian time (fig. 1) were modified during the Pennsylvanian. The regional depositional surface in early Pennsylvanian time was tilted down to the south, and a general northward thinning resulted from the overlap of that surface by Pennsylvanian rocks. More localized elements that formed during the Pennsylvanian appear, in contrast, to trend roughly north, for example, the Pedernal, Sierra Grande, Uncompahgre, Joyita, and Penasco Uplifts (fig. 7). However, the Bravo Dome and Matador Arch on the east side of the State are east-trending uplifted features, whereas Central Basin Platform is essentially aligned north-south. The Zuni, Florida, and Cimarron Uplifts had northwest trends. In the Sangre de Cristo Mountains area, more than 2,300 m of Pennsylvanian clastic sediments were deposited in a deep north-trending structural basin called the Rowe-Mora Basin by Read and Wood (1947) and the Taos Trough by Sutherland (1963). A southeastern extension of the Paradox Basin into northwestern New Mexico during Pennsylvanian time was connected southeastward with a chain of small basins that connected southward with the Orogrande Basin; the Orogrande Basin occupied an area along the west side of the Pedernal Uplift and extended southward into Texas. The Delaware Basin in the southeast, the Pedregosa Basin in the southwest, and the Orogrande Basin in south-central New Mexico were areas of thick deposition throughout Pennsylvanian time.

STRUCTURAL EVENTS FOLLOWING PENNSYLVANIAN DEPOSITION

In the Rowe-Mora Basin area of north-central New Mexico, a thick sequence of nonmarine red beds and arkoses of the Sangre de Cristo Formation was deposited in late Pennsylvanian and Wolfcampian time indicating uplift and erosion of the bounding uplifts. Similarly, as part of the Rocky Mountain orogeny, in south-central New Mexico, the Pedernal Uplift was active in early Permian; it remained as a highland in local areas until middle Permian time, as shown by areas such as Pedernal Mountain and Pajarito Mountain, where Precambrian rocks are overlapped by Abo red beds, the Yeso Formation, and the San Andres Limestone of Leonardian and early Guadalupian age. Laramide structural deformation greatly affected the State; overthrust belts formed in southwestern New Mexico. Present distribution of Pennsylvanian rocks has been greatly affected by basin-and-range faulting during Miocene to Holocene time. Much of this late Cretaceous-early Tertiary and middle and late Cenozoic structural deformation appears to have been controlled somewhat by the features of Pennsylvanian and early Permian age. For example, the Rio Grande rift is subparallel to the string of central New Mexico Pennsylvanian-age depositional basins that ran essentially from the southeast corner of the San Juan Basin area southward into south-central New Mexico.

LITHOSTRATIGRAPHY

LITHOSTRATIGRAPHIC SUBDIVISIONS

Gordon (1907) proposed the term Magdalena Group for all the sedimentary rocks in central New Mexico above the Mississippian and below the Abo red beds, which are the basal Permian. The unit in places is synonymous with Pennsylvanian, but in other areas, it has been used to include Mississippian rocks at the base and (or) Wolfcampian rocks at the top.

Gordon divided the Magdalena Group into a lower clastic phase, the Sandia Formation, and an upper carbonate phase, the Madera Limestone. In many areas, the Madera was subdivided into a lower limestone member and an upper arkosic limestone member. In addition, at the top of the Magdalena Group in central New Mexico, is the Bursum Formation, which in most areas is entirely of Wolfcampian age.

In the Silver City mining district of southwestern New Mexico, Spencer and Paige (1935) used the term Magdalena Group; however, they divided the group into a lower Oswaldo Formation and an upper Syrena Formation, which were roughly comparable to the Sandia and Madera units. Thompson (1942, 1948) divided the Pennsylvanian into correlatives of the Des Moines, Missouri, and Virgil Series and introduced a new series, Derry, for the pre-Des Moines strata in the southern part of the State. He subdivided each series into two groups and then into thin formations on the basis of rock types and fusulinid zonation.

Geologic mapping of isolated mountain ranges in New Mexico has led to a nomenclature being used in each range that is somewhat distinct from the general classification. The terms "Sandia" and "Madera" have been used in north-central New Mexico in the Sangre de Cristo Mountains, although in the vicinity of Pecos, Sutherland (1963) combined rocks equivalent to the Sandia and the lower member of the Madera into the La Pasada Formation. Because to the north, facies of this unit are different, he applied the name Flechado Formation to the rocks generally equivalent to the La Pasada to the south. The upper member of the Madera was called the Alamitos Formation by Sutherland, and the uppermost Pennsylvanian rocks are in the lower part of the Sangre de Cristo Formation in this area. In the San Juan Basin region, where essentially all the Pennsylvanian units are in the subsurface in New Mexico but crop out north of Durango, Colo., on the edge of the San Juan Mountains, the Atokan part of the Pennsylvanian is the Molas Formation and is overlain by the Hermosa Group (fig. 8). The Hermosa Group consists of, in ascending order, the Pinkerton Trail Formation, the Paradox Formation, and the Honaker Trail Formation.

In the Lucero Mesa area southwest of Albuquerque, Kelley and Wood (1946) mapped the Sandia Formation and Madera Limestone and divided the

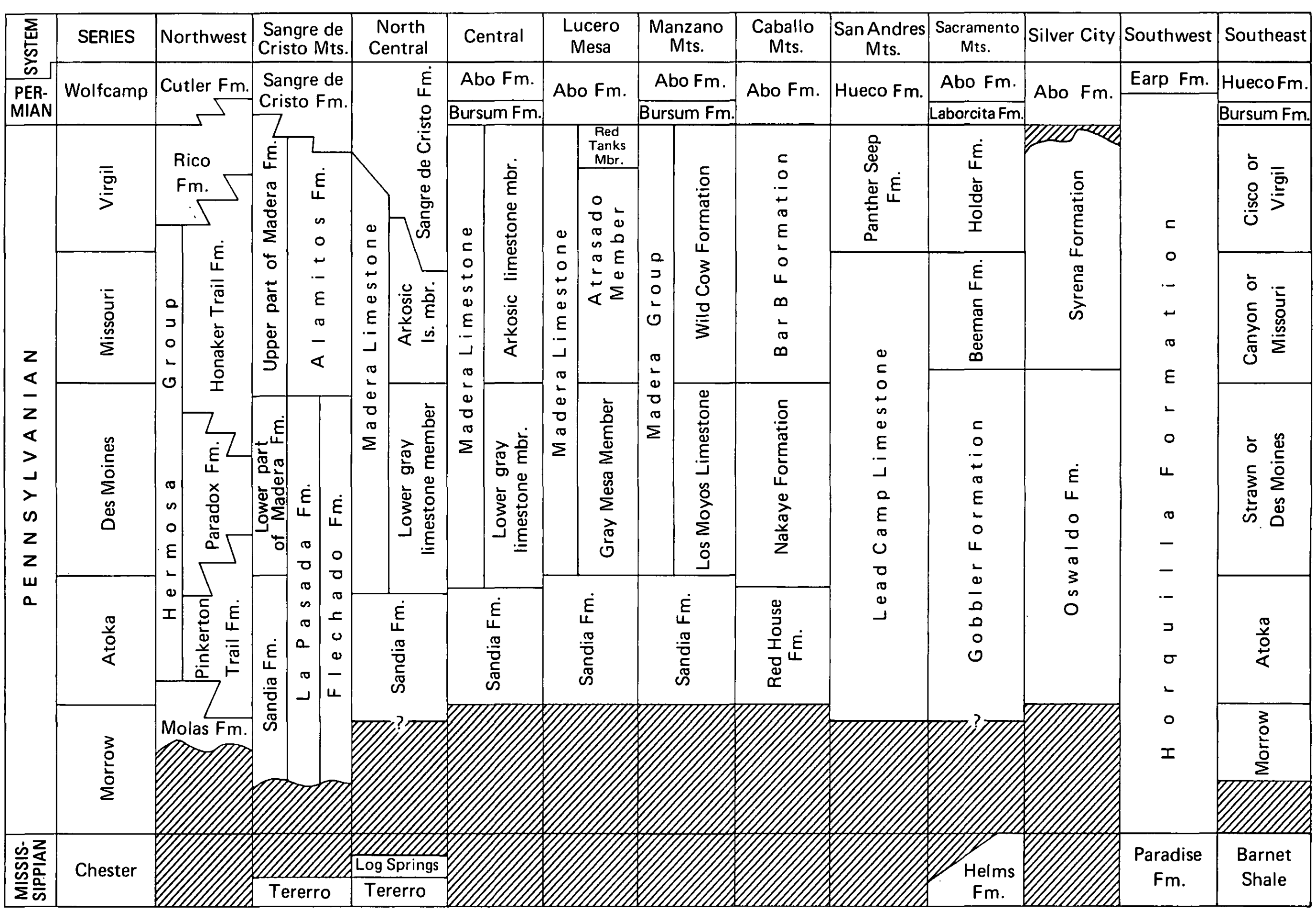


FIGURE 8.—Correlation chart of Pennsylvanian rocks of New Mexico.

Madera into the Gray Mesa Member at the base, the middle Atrasado Member, and the upper Red Tanks Member. Myers (1973) recently mapped in the Manzano Mountains area, southeast of Albuquerque; he retained the use of the Sandia Formation and raised the Madera to a group that includes at its base the Los Moyos Limestone and at its top, the Wild Cow Formation. He divided the Wild Cow into three members. Kelley and Silver (1952), in their mapping of the Caballo Mountains in south-central New Mexico, used essentially the threefold division of Sandia, Madera Limestone, and upper clastic units of the Madera. However, they named their map units, in ascending order, the Red House, Nakaye, and Bar B Formations. In the Sacramento Mountains area of south-central New Mexico, Pray (1954, 1961) divided the Pennsylvanian into the Gobbler, Beeman, and Holder Formations, in ascending order. In general, the Gobbler Formation is correlative with the Sandia and the lower part of the Madera Limestone, and the Beeman and Holder Formations are correlative with the upper arkosic limestone member of the Madera.

In the subsurface in the Delaware Basin area and adjoining marine shelves, lithic subdivisions have not generally been used; the strata have been referred mainly to series by utilizing the Midcontinent (or Texas) series names and thus have been labeled as rocks of Morrowan, Atokan (or Bend), Des Moinesian (or Strawn), Missourian (or Canyon), and Virgilian (or Cisco) age. In southwesternmost New Mexico, in the Big Hatchet, Animas, and Peloncillo Mountains, the Pennsylvanian has been referred to the Horquilla Formation, which in that area also includes Wolfcampian beds in its upper part. In the San Andres Mountains area of south-central New Mexico, the lower part of the Pennsylvanian has been called the Lead Camp Limestone of Bachman and Myers (1975), which includes equivalents of the Sandia Formation and the lower part of the Madera Limestone; the upper units are mapped in the Panther Seep Formation.

PRINCIPAL ROCK TYPES

Generally speaking, the Pennsylvanian sequence consists of a lower clastic unit roughly 150 m thick, a middle limestone unit 200–300 m thick, and an upper 150-m-thick unit of interbedded limestone and shale containing red beds near the top of the Pennsylvanian. In the Sangre de Cristo Mountains, the basal Sandia Formation consists mainly of shale, siltstone, and fine-grained to very coarse grained sandstone in varying proportions. In most of the area, shale beds form the greatest part of the Sandia, and most of these shales, even those containing marine fossils, are carbonaceous. Some coal beds and thin marine limestones are minor constituents; in the eastern part of the area, coarse arkosic sandstones are common in the Sandia Formation. The lower member of the Madera Formation in the southern and southeastern part of the mountains is characterized by light-gray marine limestones, many of them biostromal or biohermal, and interbedded calcareous shale and some thin sandstones. Northward in the Sangre de Cristo Mountains, limestones become subordinate, and thick arkosic sandstones and thick calcareous shales become major constituents. The upper part of the Madera Formation and the Alamitos Formation consist of varying proportions of red, greenish-gray, and gray shale, coarse-grained arkosic sandstone, green limestone, and nodular limestone.

Outcrops in the central part of the State in the Sandia, Manzano, and Los Pinos Mountains, Lucero Mesa, and Magdalena Mountains show a typical sequence of a lower clastic unit, middle limestone unit, and upper interbedded limestone and clastic unit. A similar sequence is seen in the southern and south-central part of the State, in the Caballo, San Andres, Sacramento, and Robledo Mountains as well as in the northern Franklin Mountains. However, the upper clastic unit, the Panther Seep Formation in the San Andres Mountains and the Beeman and Holder Formations in the Sacramento Mountains, is as much as 750 m thick. This upper clastic unit was deposited in or near the Orogrande Basin on the west side of the Pedernal Uplift and is lithologically distinct from beds typical of this part of the section in surrounding parts of New Mexico. Deposits are deltaic to brackish-water clastic rocks and precipitates, all deposited in relatively shallow waters; they include silty brownish shales, dark carbonaceous shales, dark-gray argillaceous limestones, laminated calcilutites, silty calcarenites, silty calcareous sandstone, thick lenses of massive biostromal limestone, and numerous biohermal reefs. Two thick gypsum beds are near the top of this sequence in south-central New Mexico.

In the southwestern panhandle of New Mexico, especially in the Big Hatchet Mountains area, the Pennsylvanian rocks are included with an overlying conformable unit of lower Wolfcampian age in the Horquilla Limestone and are conformable on Chesterian strata. This formation is about 700 m thick; the shelf facies consists dominantly of limestone; some interbedded siltstones are in the lower part. Along the margin of the Alamo Hueco-Pedregosa Basin (Zeller, 1965) to the southwest, porous dolostones are interlayered with limestones. In the deep-marine-basin facies, argillaceous limestone and mudstone are dominant.

FACIES CHANGES

The Pennsylvanian sections of central New Mexico were the first to be studied by geologists because they are near the populous Rio Grande Valley and also are near some of the early mining districts. In this limited area, the Pennsylvanian appeared to be relatively uniform. However, when Read and Wood (1947) and Thompson (1948) traversed from Pennsylvanian uplifts into the large basins, abrupt facies changes became obvious.

In the Sangre de Cristo Mountains, the Sandia Formation is a suite of mixed marine and nonmarine sedimentary rocks. In the southern part of the area, the Sandia is relatively thin but thickens greatly northward into the Rowe-Mora Basin; the proportion of black shale increases markedly from shelf to basin. In the southern part of the Sangre de Cristo Mountains, the lower member of the Madera Formation is mainly biohermal and biostromal limestone and contains lesser amounts of gray shale and thin sandstone, indicating a shallow-marine environment. Northward, the equivalent rocks grade into a facies in which dark-gray shale predominates and in which arkoses become conspicuous constituents. In the upper member of the Madera and the equivalent Alamitos Formation are mixed-marine and nonmarine deposits; marine limestone and shale are the predominant constituents in the south, but thick arkoses and red beds are predominant in the north.

In the southwestern panhandle, outcrops in the Big Hatchet Mountains are predominantly shallow-marine shelf limestone. Along the shelf margin, porous dolostone is interbedded with the limestone. To the south in the Alamo Hueco Basin, the facies changes into deep-marine basinal limestone and mudstone.

In south-central New Mexico, the lower part of the Pennsylvanian sequence in the Sacramento Mountains, on the west flank of the Pedernal Uplift, is similar to that in the San Andres Mountains 65 km to the west on the west side of the Orogrande Basin. However, the overlying strata of Missourian and Virgilian age in the Sacramento Mountains are feldspathic sandstone, limestone, and shale, and discontinuous algae reefs and upper reddish marl, nodular limestone, and whitish massive limestone. This facies contrasts greatly with the Orogrande Basin deposits in the Panther Seep Formation of the San Andres Mountains. These deposits include many types of fine-grained shales, siltstones, and sandstones as described above. On the edge of the Pedernal Uplift in the northern Sacramento Mountains, Otte (1959) determined the order of facies, from west to east (toward the landmass), to be: (1) massive marine limestone, (2) nodular argillaceous fusulinid-bearing limestone, (3) silty limestone containing shallow-marine fossils such as mollusks and brachiopods, (4) dolomitic limestone, (5) green calcareous shale, and (6) marine to nonmarine red shale and other terrigenous clastic rocks.

Similar facies changes exist on the east side of the Pedernal Mountains from the shelf into the Delaware Basin area. Pennsylvanian rocks do not crop out in southeastern New Mexico but have been explored by thousands of oil tests in that area.

ENVIRONMENTS OF DEPOSITION

Throughout New Mexico, depositional environments during Pennsylvanian time were strongly influenced by their tectonic positions relative to the subsiding basins and rising uplifts. The major subsiding elements were the Paradox Basin, the Rowe-Mora Basin, a central New Mexico basinal area, the Orogrande Basin, the Pedregosa Basin (Greenwood, Kottlowski, and Thompson, 1977), and the Delaware Basin. The depositional areas between the basins and the uplifts ranged from wide, tectonically stable shelves to narrow unstable belts where terrigenous deposits predominated and intertongued basinward with marine limestone and dark carboniferous basinal deposits.

In such a sedimentary framework, a wide variety of terrigenous and nonterrigenous sediments was deposited. Outcrops and subsurface data show examples of nearshore deposits including: (1) swamp and marsh deposits consisting of dark, organic-rich, carbonaceous, bioturbated claystone containing a few silt laminae and a little well-preserved plant debris; (2) tidal-flat sand and mud; (3) mud and sand indicative of overbank and channel deposition associated with small, nearshore deltaic complexes; and (4) bioturbated, muddy sediments containing sandy layers indicative of lagoonal conditions. Shelf environments are shown by carbonate wackestone and mudstone and terrigenous sandstone and mudstone. Dark carbonate mudstone, bedded with dark clay-shale admixed with carbonate deposits or forming thin distinct layers, also is present at some localities and reflects deeper basin sedimentation.

BIOSTRATIGRAPHY

AGE OF ROCKS

In all quadrants of the State, the standard Pennsylvanian series, Morrow, Atoka, Des Moines, Missouri, and Virgil, are present. However, in places, particularly along the flanks of uplifts, the entire Morrowan or its lower part is absent. In other areas, the uppermost part of the Virgilian is missing. The most complete section is in the Big Hatchet Mountains area of southwestern New Mexico, where all the Pennsylvanian series are present in a dominantly carbonate-rock sequence and where contacts with the underlying Chesterian and overlying Wolfcampian units are conformable.

FAUNAL SUCCESSION AND ASSIGNMENT OF SERIES

Marine rocks are dominant in the Pennsylvanian sequences in New Mexico, and marine invertebrate fossils are abundant throughout most of the sections. Fusulinids provide the main basis for the assignment of series boundaries and correlation of biostratigraphic units. In some areas, the brachiopod faunas have been described in detail, particularly in the Sangre de Cristo Mountains by Sutherland (1963) and Sutherland and Harlow (1973).

Morrowan rocks contain a distinctive fauna of *Eostaffella* and *Millerella* which differ from the same genera in the lower part of the Atokan. The Atokan series is divided into a lower zone on the range of the genus *Profusulinella* and into an upper zone on the range of *Fusulinella.* Des Moinesian rocks are marked by *Beedeina* and *Wedekindellina.* Missourian beds are marked by more primitive forms of the genus *Triticites* and by *Eowaeringella.* The biozone of *Eowaeringella* is one of the best defined and most restrictive fusulinid zones (Stewart, 1968, 1970) and is present near the base of the Missourian series. Virgilian rocks are distinguished by the ranges of certain species *Triticites,* by *Dunbarinella,* and by certain species of *Pseudofusulinella. Triticites* ranges up into the lower part of the overlying basal Permian (Wolfcampian) series; *Schwagerina, Pseudofusulina,* and *Leptotriticites* occur in the lower part of the Wolfcampian and extend up into younger Permian but do not occur in Virgilian rocks. Wilde (1975) has systematically studied the fusulinids in the Big Hatchet Mountains section and places the Pennsylvanian-Permian boundary on the basis of the evolutionary development of various species of *Triticites* and at the first appearance of *Leptotriticites* and (or) *Schwagerina.*

IGNEOUS AND METAMORPHIC ROCKS

No igneous rocks of Pennsylvanian age are known in New Mexico, although some of the Missourian shales in the area east of Socorro are bentonitic, indicating their possible derivation from volcanic ash. In many mining districts, Pennsylvanian rocks have been metamorphosed by Laramide- and Cenozoic-age intrusions and, along with the Mississippian rocks, are hosts for some of the base-metal ore deposits.

ECONOMIC PRODUCTS

COAL

Scattered lenses of coal are present in the lower part of the Pennsylvanian in the Sangre de Cristo Mountains. In general, these coal lenses are in the shoreline deposits on the east and west sides of the Rowe-Mora Basin and are in beds ranging in age from Atokan to Des Moinesian. Some of the coal lenses are as much as 2 m thick but are very local in extent. This coal was used only in homes and in small limestone kilns. Thin coal beds and coal laminae are present in Virgilian strata in the Sandia and Manzano Mountains; they are intercalated with red beds and marine limestone in shoreline deposits on the west side of the Pedernal Uplift.

Lenses of coal have been found in oil tests on the northwest shelf of the Delaware Basin amid the deltas and along the irregular coastlines of the shallow seas that bordered the Pedernal Uplift on the east and southeast during the Pennsylvanian. These coal lenses are associated with barrier-bar and point-bar stream-channel sandstones and with clay and silty flood-basin deposits. Most of these thin coal lenses (detected only by drilling) are Morrowan or Atokan in age. During early Pennsylvanian time, this area may have been dominated by large deltas similar to those of the Illinois Basin.

PETROLEUM RESOURCES

Prolific production of oil has been obtained from Pennsylvanian reservoirs in the Delaware Basin area of southeastern New Mexico and in the San Juan-Paradox Basin of northwestern New Mexico. Annual production from Pennsylvanian rocks reached its height of about 27 million barrels per year in 1969 and has dropped off since then to a little more than 7 million barrels in 1976. Cumulative production from the Pennsylvanian reservoirs in the State (fig. 9) is about 260 million barrels.

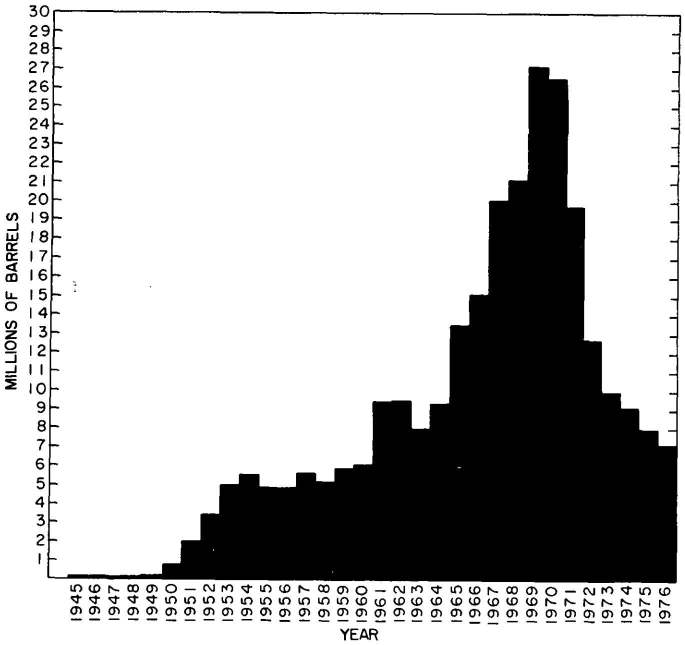


FIGURE 9.—Amount of crude oil produced from Pennsylvanian reservoirs in New Mexico, 1945–1976. Data from Roy W. Foster (written commun., 1978).

Production from Mississippian rocks is restricted mainly to southeastern New Mexico and the Delaware Basin area; peak production was in 1960 when 80,000 barrels was produced from Mississippian rocks. The last production of any significance from Mississippian strata was in 1972 when about 20,000 barrels was produced. The cumulative production from the Mississippian for New Mexico has been about 450,000 barrels.

Pennsylvanian rocks are a major source of natural gas in southeastern New Mexico. In 1976, production from these reservoirs was about 300 billion cubic feet. However, an accurate estimate of total natural gas produced from Pennsylvanian reservoirs is difficult to obtain because many wells are multiple completions in Pennylvanian as well as in older and younger rocks. Most of the natural gas from the Middle and Upper Pennsylvanian is casinghead gas (produced with crude oil). Most of the gas produced from lenticular sandstone bodies in the deltaic Morrowan sequences of the Delaware Basin is dry gas.

METALLIC ORES

Some of the red beds in Upper Pennsylvanian units, particularly in the north-central part of the State, contain scattered deposits of copper sulfides and carbonates. These are present mostly as nodules and as disseminated grains associated with small amounts of uranium and vanadium in arkose, green and gray shale, and nodular limestone (Zeller and Baltz, 1954). In the base-metal mining districts of central and southwestern New Mexico, Pennsylvanian limestones are host for some replacement deposits. They are also fractured and faulted and contain vein and stocklike metallic deposits. In most areas, however, the purer crinoidal limestones of the Mississippian are more favorable horizons for replacement deposits than the Pennsylvanian. The Carboniferous limestone sequence is also host to vein and breccia deposits of fluorite-barite-galena in south-central and central New Mexico where locally massive crystalline limestones have been selectively replaced.

LIMESTONE AND OTHER NONMETALLIC MINERALS

Throughout the State where Carboniferous limestone crops out, it is used locally for manufacture of cement (as at Tijeras east of Albuquerque), road metal, flagstone, lime, and dimension stone. Production of road metal is by far the largest use of Mississippian and Pennsylvanian limestones. Fossiliferous flagstones of Pennsylvanian limestone were placed in the courtyard of the Palace of Governors in Santa Fe almost four centuries ago.

Clay and shale of the Pennsylvanian have been used locally to make brick and tile, although for the most part, the argillaceous rocks are too highly calcareous. In south-central New Mexico, in the San Andres, Organ, and northern Franklin Mountains, gypsum beds in the upper part of the Pennsylvanian have been used locally in the manufacture of cement and as a soil conditioner. Some of the more even-bedded Pennsylvanian sandstones have been used in minor amounts for flagstones and for building some of the ancient dwellings.

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2001

The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1110–M–DD

ON THE COVER

Swamp-forest landscape at time of coal formation: lepidodendrons (left), sigillarias (in the center), calamites, and cordaites (right), in addition to tree ferns and other ferns. Near the base of the largest *Lepidodendron* (left) is a large dragonfly (70-cm wingspread). (Reproduced from frontispiece in Kukuk, Paul (1938), "Geologie des Niederrheinisch-Westfälischen Steinkohlengebietes" by permission of Springer-Verlag, New York, Inc.)

The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—

M. Iowa, by Matthew J. Avcin and Donald L. Koch
N. Missouri, by Thomas L. Thompson
O. Arkansas, by Boyd R. Haley, Ernest E. Glick, William M. Caplan, Drew F. Holbrook, and Charles G. Stone
P. Nebraska, by R. R. Burchett
Q. Kansas, by William J. Ebanks, Jr., Lawrence L. Brady, Philip H. Heckel, Howard G. O'Connor, George A. Sanderson, Ronald R. West, and Frank W. Wilson
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DD. Alaska, by J. Thomas Dutro, Jr.

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CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, ***Director***

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FOREWORD

The year 1979 is not only the Centennial of the U.S. Geological Survey—it is also the year for the quadrennial meeting of the International Congress on Carboniferous Stratigraphy and Geology, which meets in the United States for its ninth session. This session is the first time that the major international congress, first organized in 1927, has met outside Europe. For this reason it is particularly appropriate that the Carboniferous Congress closely consider the Mississippian and Pennsylvanian Systems; American usage of these terms does not conform with the more traditional European usage of the term "Carboniferous."

In the spring of 1976, shortly after accepting the invitation to meet in the United States, the Permanent Committee for the Congress requested that a summary of American Carboniferous geology be prepared. The Geological Survey had already prepared Professional Paper 853, "Paleotectonic Investigations of the Pennsylvanian System in the United States," and was preparing Professional Paper 1010, "Paleotectonic Investigations of the Mississippian System in the United States." These major works emphasize geologic structures and draw heavily on subsurface data. The Permanent Committee also hoped for a report that would emphasize surface outcrops and provide more information on historical development, economic products, and other matters not considered in detail in Professional Papers 853 and 1010.

Because the U.S. Geological Survey did not possess all the information necessary to prepare such a work, the Chief Geologist turned to the Association of American State Geologists. An enthusiastic agreement was reached that those States in which Mississippian or Pennsylvanian rocks are exposed would provide the requested summaries; each State Geologist would be responsible for the preparation of the chapter on his State. In some States, the State Geologist himself became the sole author or wrote in conjunction with his colleagues; in others, the work was done by those in academic or commercial fields. A few State Geologists invited individuals within the U.S. Geological Survey to prepare the summaries for their States.

Although the authors followed guidelines closely, a diversity in outlook and approach may be found among these papers, for each has its own unique geographic view. In general, the papers conform to U.S. Geological Survey format. Most geologists have given measurements in metric units, following current practice; several authors, however, have used both metric and inch-pound measurements in indicating thickness of strata, isopach intervals, and similar data.

FOREWORD

This series of contributions differs from typical U.S. Geological Survey stratigraphic studies in that these manuscripts have not been examined by the Geologic Names Committee of the Survey. This committee is charged with insuring consistent usage of formational and other stratigraphic names in U.S. Geological Survey publications. Because the names in these papers on the Carboniferous are those used by the State agencies, it would have been inappropriate for the Geologic Names Committee to take any action.

The Geological Survey has had a long tradition of warm cooperation with the State geological agencies. Cooperative projects are well known and mutually appreciated. The Carboniferous Congress has provided yet another opportunity for State and Federal scientific cooperation. This series of reports has incorporated much new geologic information and for many years will aid man's wise utilization of the resources of the Earth.

H. William Menard
Director, U.S. Geological Survey

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