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

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

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

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ABSTRACT

Carboniferous rocks in Arizona are represented by marine and continental deposits ranging in thickness from 0 to 1,100 m. Mississippian marine strata, consisting largely of cliff-forming high-purity limestone, are overlain disconformably by thicker Pennsylvanian strata containing, besides carbonate rocks, varying proportions of siliceous clastic deposits.

The two contrasting outcrop regions are: (1) a northeast or Plateau half, where exposures are limited largely to deep canyons and escarpments; and (2) a southwest or Basin and Range half, where exposures are found only in certain discontinuous range blocks.

Shallow Mississippian seas first transgressed the Arizona region from the northwest and southeast in Kinderhookian time. Strata as young as Chesterian are preserved only locally, an unknown thickness of Upper Mississippian rocks having been removed before the onset of Pennsylvanian sedimentation.

During Pennsylvanian time, northern Arizona was flanked by marine basins to the west, northeast, and southeast, the central part receiving a relatively thin zone of clastic deposits. Precambrian granitic source rocks were exposed on the Defiance positive area in east-central Arizona and were partly onlapped by Pennsylvanian deposits, at least during Missourian and Virgilian time. Faulting during the Pennsylvanian probably gave magnified expression to the southwest margin of this feature.

Carboniferous rocks, chiefly limestone, contributed to products valued at more than $50 million during 1977. Principal commodities were portland cement and quicklime. The welfare of almost every Arizona resident is enhanced by the State's Carboniferous rocks.

INTRODUCTION

DISTRIBUTION AND GENERAL CHARACTERISTICS

Known Carboniferous rocks in Arizona consist only of sedimentary materials. In the Plateau region of northern Arizona, most of these rocks, except for two linear belts of exposures represented by (1) the Grand Canyon and (2) the southern cliffs margin of the Plateau, are buried beneath either Paleozoic or Paleozoic and Mesozoic strata. In the southern half of the State, the Basin and Range part, outcrops are limited to relatively short linear strips within certain mountain or range blocks, especially those in southeastern Arizona. Very little is known of the subsurface nature and distribution of these rocks within the valley, or basin, blocks. Overall, only a very small percentage of the Arizona surface environment is covered with rocks of Carboniferous age. This small percentage is, in turn, unequally distributed (fig. 1).

The most continuous outcrop belt of Carboniferous rocks in Arizona is in the Grand Canyon, a product of late Cenozoic erosion by the Colorado River. Here, because the strata are nearly flat-lying and relatively undeformed, each layer imparts its own set of strengths and weaknesses to form the topographic profile. In particular, the Mississippian strata form one of the more prominent cliffs throughout Grand Canyon, whereas the overlying Pennsylvanian strata support both ledges and slopes. Along the southern edge of the Plateau province, various erosional events have exposed Carboniferous strata. Because of a slight northeast dip, probably imposed initially in Mesozoic time, older strata were truncated southward, and Carboniferous and other rocks were exposed in Mesozoic time. Although several subsequent tectonic-erosional episodes took place, the principal deep canyons that now are being cut into the Plateau edge were initiated during the late Cenozoic (Peirce and others, 1976), probably as a response to drainage integration in contrast to concurrent so-called Plateau uplift, as hypothesized by McKee and McKee (1972).

South of the Plateau, in the Basin and Range region, Carboniferous rocks were subjected to severe tectonic disturbances during Mesozoic and Cenozoic times. Several episodes of plutonism are known, and, locally, Carboniferous strata have been metamorphosed and mineralized. Flat-lying strata are rare, steep dips being the general rule. The present

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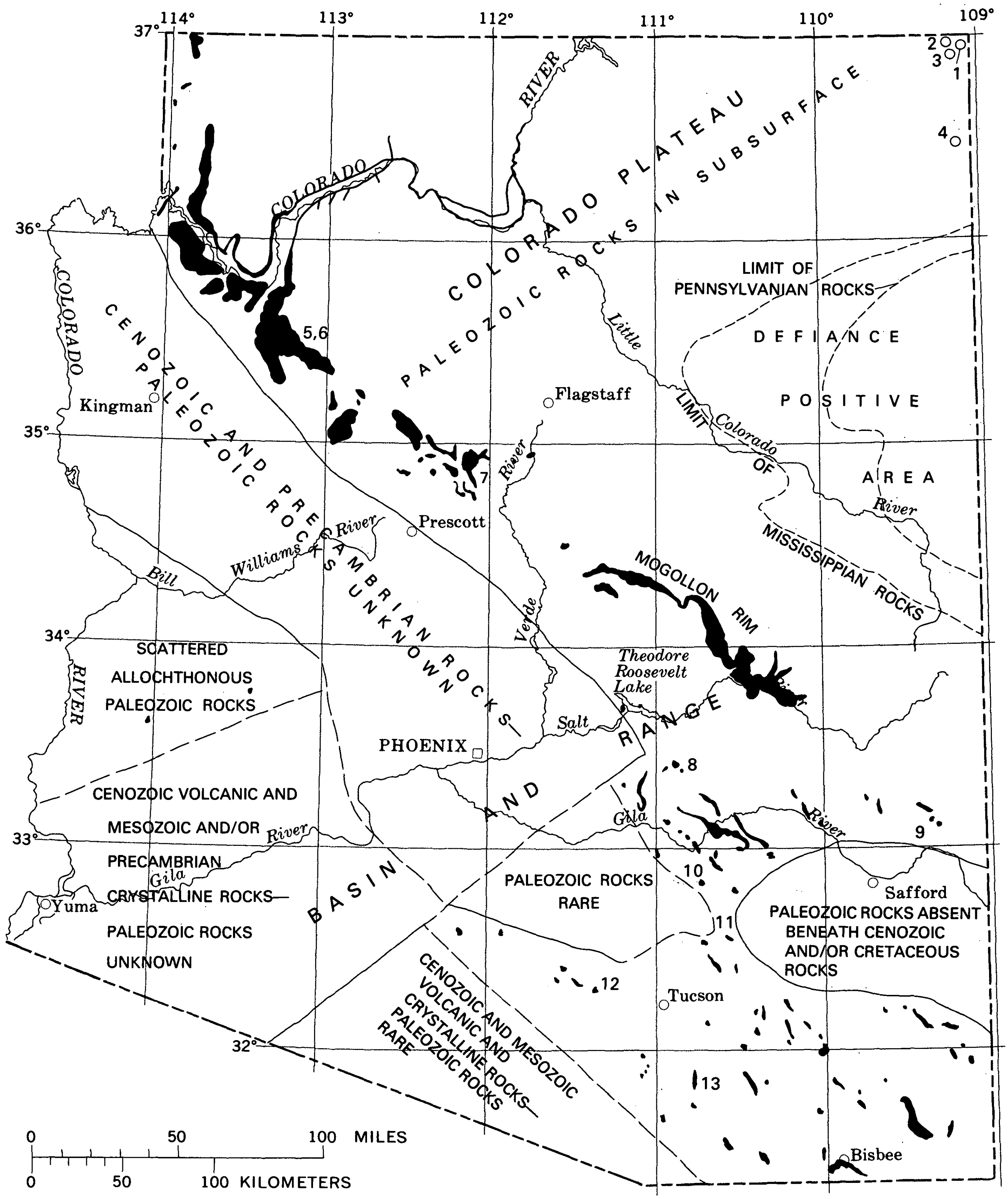

FIGURE 1.—Carboniferous outcrops, distribution of Paleozoic and other rocks, and primary sources of Carboniferous products (numbered and listed in table 1). Areas of broad geologic similarity shown as solid lines; long dashes where inferred. Zero isopach for Mississippian and for Pennsylvanian rocks in northeast part of State shown by short dashed line.

physiographic pattern of disconnected ranges and basins is largely the result of late Cenozoic extensional tectonics. Where present in this province, as in the Plateau province, the Mississippian strata form prominent cliffs, and the Pennsylvanian strata form ledges and slopes.

HISTORICAL REVIEW AND USE OF "CARBONIFEROUS"

The term "Carboniferous" is no longer widely used in Arizona because: (1) the Mississippian and Pennsylvanian parts generally are separable and mappable; (2) their respective histories are notably different; and (3) the top of the Pennsylvanian is, in most places (more so in the subsurface), imprecisely defined.

Arizona Carboniferous rocks initially were included in studies undertaken in two widely separated regions: (1) in northern Arizona at Grand Canyon because of conspicuous exposures, and (2) in southern Arizona mining camps where many of these rocks are associated with ore development.

In 1875, Gilbert gave the name "Red Wall Limestone" to more than 610 m (2,000 ft) of Grand Canyon strata. Apparently, this interval included rocks ranging in age from Devonian to, and perhaps including, Permian. Subsequent refinement by Darton (1910) and Noble (1922) led to the presently prevailing restriction of this name (now Redwall) to strata of Mississippian age. Overlying Pennsylvanian-Permian(?) strata were, in turn, designated "Supai Formation."

In extreme southern Arizona, in the Bisbee quadrangle, Ransome (1904) defined a Carboniferous section as consisting of about 1,128 m (3,700 ft) of combined Mississippian "Escabrosa limestone" (61 m) and Pennsylvanian "Naco limestone" (900 m or more). Subsequently, upon recognition of Permian strata, the "Naco limestone" of Ransome has been altered and restricted.

In 1905, Lindgren, in discussing the mineralized Clifton quadrangle in east-central Arizona, recognized Carboniferous strata. Although outcrops are limited, he defined two outcrop sequences: (1) one to the south exposing about 52 m of Mississippian strata (beneath Mesozoic rocks) to which, apparently, he assigned the name "Modoc limestone" although, in his discussion, he uses "formation" and "limestone" interchangeably, and (2) one to the north exposing about 152 m (500 ft) of strata underlying Tertiary rocks. To this sequence he applied the name "Tule Spring limestone," recognizing that the lower 61 m is Mississippian in age, and the upper 91 m, Pennsylvanian. Whereas this terminology has been applied only locally, the Grand Canyon and southern Arizona terminologies, in contrast, have been applied over much of the Plateau and Basin and Range provinces.

Ransome (1916) attempted to tie together Arizona Paleozoic stratigraphy by correlating sections from Grand Canyon on the north to Bisbee in extreme southern Arizona. He defined a Carboniferous "Tornado limestone" in the Globe-Ray region of central Arizona. He recognized a Mississippian lower massive part and a Pennsylvanian upper part but did not draw a contact in between. He further noted an analogy between the "Tornado limestone" and the Escabrosa-Naco limestones of the Bisbee region. Subsequently, the use of "Tornado limestone" has been replaced by Ransome's original Bisbee area terminology.

Darton (1925) gave one of the more comprehensive coverages of the general geology of Arizona. It includes a summary of the "Carboniferous System" as well as an extensive documentation of the distribution of outcrops of Mississippian and Pennsylvanian strata. Much of the data presented was an outgrowth of fieldwork done cooperatively by the U.S. Geological Survey and the Arizona Bureau of Mines in connection with the first (Darton, 1924) State geologic map of Arizona.

While a professor at the University of Arizona, Stoyanow (1926; 1936), assisted by students seeking advanced degrees (as well as those who worked during summer field seasons with the Arizona Bureau of Mines' geologic program), undertook to establish regional relationships of Paleozoic rocks in Arizona. Although much of the early paleontological work should be credited to G. H. Girty of the U.S. Geological Survey, Stoyanow, also a paleontologist, examined and interpreted the significance of the paleontological highlights of the Carboniferous strata of the State.

McKee (1951) made further paleogeographic interpretations over the entire State, including those relating to Mississippian and Pennsylvanian rocks. Havenor (1958) gave special emphasis to a review of the Pennsylvanian sedimentation framework in Arizona. Most recently, Purves (1976) has initiated a study and review of the Mississippian System of Arizona. In addition to a comprehensive review of past studies, he has presented a list of 33 Basin and Range mountain blocks and other localities in which work on Mississippian strata has been done. Purves is attempting to refine statewide time-facies boundaries by rigorous conodont zonation and petrographic studies.

Many important later contributions have been made by studies of regions of lesser size than the State. Most such studies focus on either the Mississippian or Pennsylvanian systems and not on a "Carboniferous System." Some of these include: Jackson (1951); McNair (1951); Huddle and Dobrovolny (1952); Hughes (1952); Sabins (1957); Thomas (1959); Fetzner (1960); Kottlowski (1960); Armstrong (1962); Hammer and Webster (1962); Lokke (1962); Kottlowski and Havenor (1962); Yochelson (1962); Sabins and Ross (1963); Winters (1963); Brew (1965); Finnell (1966a, 1966b); McKee and Gutschick (1969); Lessentine (1969); Peirce and others (1970); Norby (1971); Blazey (1971); Ross (1973); Racey (1974); Smith (1974); Conyers (1975); McKee (1975a, 1975b); Kent (1975); Peirce and others (1977); and many others.

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 Arizona Bureau of Geology and Mineral Technology.

GEOLOGIC SETTING

CONTACTS

Mississippian rocks almost everywhere overlie strata of Devonian age. In outcrop, this contact most commonly is described as showing conformity. In very few places, an erosional surface is evident and relatively thin discontinuous conglomerates are present. In turn, Pennsylvanian rocks prevailingly overlie Mississippian strata unconformably except in the subsurface near the Defiance positive area in east-central Arizona, where they overlap both Devonian strata and Precambrian granitic rocks (Peirce, 1976, p. 40).

In general, the cliffs formed by Mississippian rocks contrast markedly with the ledge-slope terrain supported by a relatively thin sequence (usually less than 200 m) of Devonian strata. In detail, the appearance of lithologic gradation often hinders identifying a precise contact. However, faunal evidence suggests that a hiatus involving at least the lowermost Mississippian generally exists. Perhaps the contact between Devonian and Mississippian rocks is most conveniently described as being a paraconformity.

The Carboniferous of Arizona generally may be divided into both Mississippian and Pennsylvanian formational components because an identifiable internal contact is present. That the contact may at times be subtle is suggested by the earlier tendency to lump these components together under one formational entity, such as Tornado limestone and Tule Spring limestone. Nevertheless, on more recent geologic maps, including the State geologic map (Wilson and others, 1969) at a scale of 1:500,000, Mississippian and Pennsylvanian strata are everywhere depicted as separate map units. Again, in outcrop, conformity is the prevailing appearance even though there generally is a hiatus involving late Mississippian and early Pennsylvanian time. In a regional sense, it seems essential that some minor angular discordance exists, at least locally. In central Arizona, a well-recognized thinning of Mississippian strata (fig. 2) is associated, at least in part, with an upper subaerially generated Paleozoic erosion surface. This surface is readily identified in most of the petroleum test holes drilled in northeastern Arizona (Peirce and Scurlock, 1972). Here, Pennsylvanian strata appear to truncate Mississippian strata along the southern part of the Defiance positive area (fig. 1). In outcrop, the Mississippian-aged cliff-forming limestones almost everywhere contrast with the ledge and slope topography of overlying Pennsylvanian strata.

Defining the top of Carboniferous, or Pennsylvanian, rocks in Arizona is a classic problem. The major stumbling block has been a paucity of critical chronological data preserved in either the highest Pennsylvanian or the lowest Permian rocks. Only one generally successful local effort has been made to define an acceptable and mappable Pennsylvanian-Permian systemic boundary, and this was by Winters (1963) in east-central Arizona. Even this boundary, though convenient, is somewhat arbitrary because of the apparent absence of diagnostic Early Permian fossil forms. More recently, McKee (1975a) redefined certain Pennsylvanian-Permian strata of a part of Grand Canyon. In so doing, he suggested that a Pennsylvanian-Permian boundary can be defined by a conglomerate that constitutes the base of Permian rocks in some sections. Elsewhere, thin conglomerate zones exist in many sections along the southern edge of the Plateau province (Peirce and others, 1977). Some are closely associated with a rather prolific record of plant fossils that appear to occupy a position close to the Pennsylvanian-Permian boundary (Blazey, 1971). Additional investigative effort may shed light on this time boundary. In

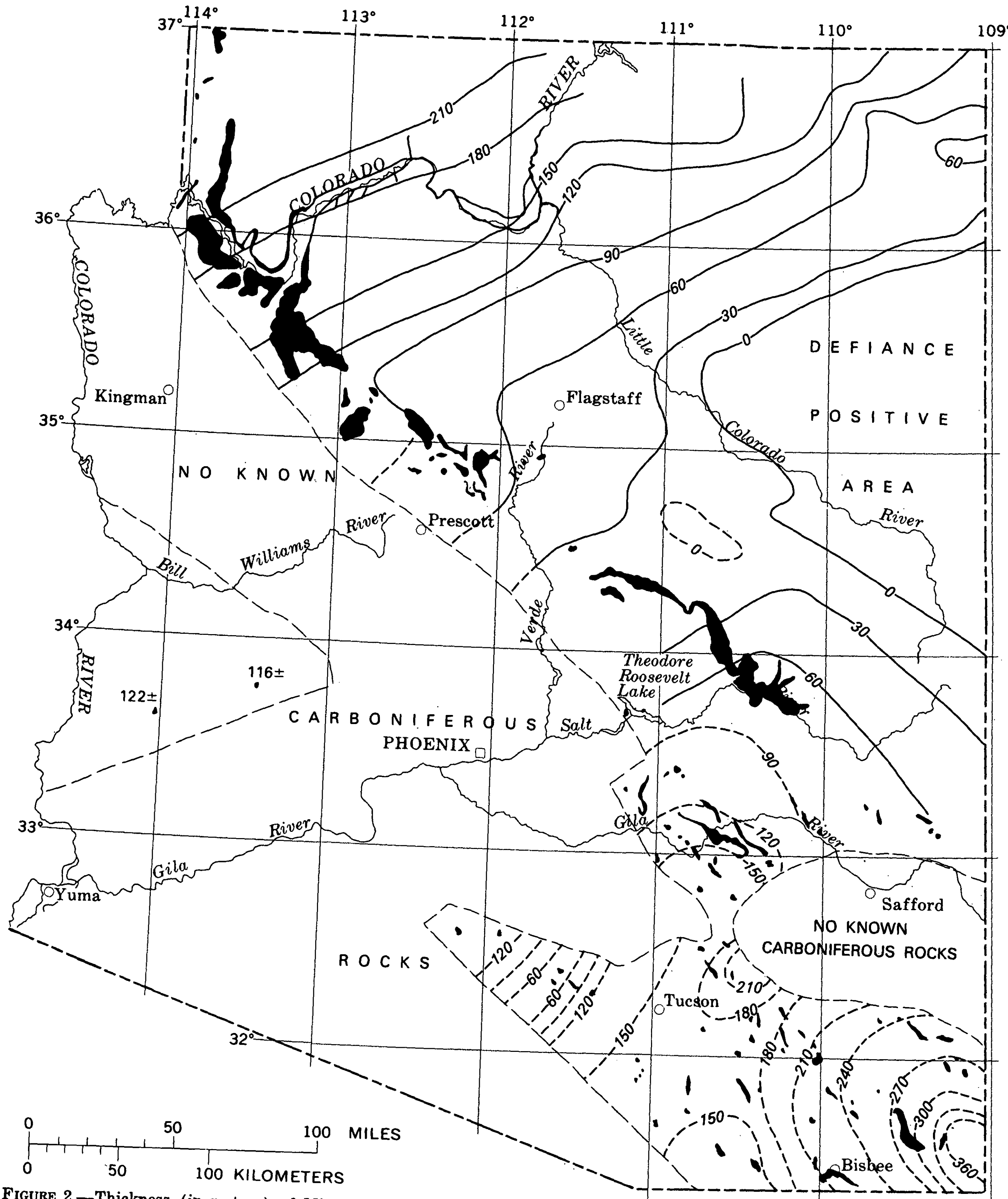

FIGURE 2.—Thickness (in meters) of Mississippian rocks as inferred from present distribution. Dashed where uncertain.

southern Arizona, the Pennsylvanian-Permian boundary is in a sequence of marine limestones that in places can be bracketed but not defined precisely. South of the Plateau is a broad region in which Pennsylvanian strata are overlain by Tertiary rocks. Overall, the upper contact between Carboniferous and Permian rocks remains vague and generally within conformable stratal sequences.

STRUCTURAL FRAMEWORK

During the Carboniferous, Arizona probably occupied a shelf position relative to two geosynclines, the Cordilleran to the west and the Sonoran to the south. Strata of both systems thin to extinction in part of east-central Arizona. A stratal comparison clearly shows that this shelf position was much more stable during the Mississippian Period than during the Pennsylvanian.

Mississippian strata consist of relatively quartz free limestones that accumulated in a shallow open-marine environment. Overall thickness variations appear to be systematic (fig. 2). McKee (1969) noted that exposures in the Grand Canyon region reflect three transgression-regression episodes ranging in age from late Kinderhookian to Chesterian, the latter record being incomplete because of later exposure and erosion. The slight earth movements that affected the deposition and subsequent regional erosion of Mississippian strata might properly be classed as epeirogenic. The thinning and absence of these strata in parts of east-central Arizona seems to be related to both nondeposition and erosion prior to the deposition of Pennsylvanian strata.

In general, Pennsylvanian rocks are thicker, more varied, more siliceous, thinner bedded, and more cyclic than Mississippian rocks. The influence of tectonism, both regional and local, on the Pennsylvanian System in Arizona contrasts markedly with the Mississippian. Thinning over a short distance onto Precambrian granitic rocks in east-central Arizona may signify faulting during the early Pennsylvanian (fig. 3). This region seems to be a southwest edge of the so-called ancestral Rockies (Eardley, 1962) that evolved during Pennsylvanian time. The principal post-Carboniferous structural events took place in Mesozoic and Cenozoic times. In Mesozoic time, a northwest-trending uplift centered southwest of the present Plateau edge, imparted a shallow northeast dip to the Plateau Paleozoic rocks. Pre-Upper Cretaceous erosion (probably Triassic and Jurassic) beveled Paleozoic strata and Precambrian rocks southward, thus exposing Carboniferous strata for the first time since original burial by Permian deposits. South of the structural high point, structural lowness may have prevailed as indicated by the preservation of much of the Paleozoic sequence in certain localities. However, local zones are present in this (once structurally low) terrain where Cretaceous deposits rest depositionally upon Precambrian crystalline rocks (Empire mountains), thus demonstrating the existence of at least local pre-Laramide deformation and erosion.

In a Late Cretaceous-early Cenozoic time, the entire State was affected by the so-called Laramide orogeny, at which time the present Rocky Mountains evolved. Plateau strata locally were folded and faulted along north- to northwest-trending fold axes of considerable length. In the south, igneous activity was widespread, ore deposits associated with much fracturing were emplaced, and, according to some, thrusting was widespread (Drewes, 1977). Carboniferous rocks were important hosts for base-metal deposits in the south, whereas, to the north, some petroleum accumulations in Carboniferous rocks were controlled by structures derived at this time.

Post-Laramide Cenozoic structural history is still being unraveled. Allochthonous blocks of Carboniferous rocks are well known in the Basin and Range province. To the extent that these blocks are associated with allochthonous Cenozoic rocks, the latest causal event must be Cenozoic in age. Preliminary evidence suggests: (1) a dislocative event during the lower Miocene between 13 and 20 m.y. ago followed by (2) the classic Basin and Range rifting event during late Miocene-Pliocene less than about 15 m.y. ago (Peirce, 1976). This latter event defined, for the most part, the structural setting that controls the broader characteristics of the contemporary landscape south of the Plateau.

GENERAL STRATIGRAPHY AND LITHOLOGY

MISSISSIPPIAN

Mississippian strata range in thickness from 0 to 380 m (1,250 ft). The greater thicknesses are in the northwest and southeast corners of Arizona; thinning to wedge-out beneath Pennsylvanian rocks (fig. 2) is found in east-central Arizona on the Defiance positive area of McKee (1951; Peirce and others, 1977, fig. 6).

In the Plateau section of Arizona, the Mississippian strata are known by the name Redwall Limestone. A formal fourfold division into members is in general use. From the base upward, these units are

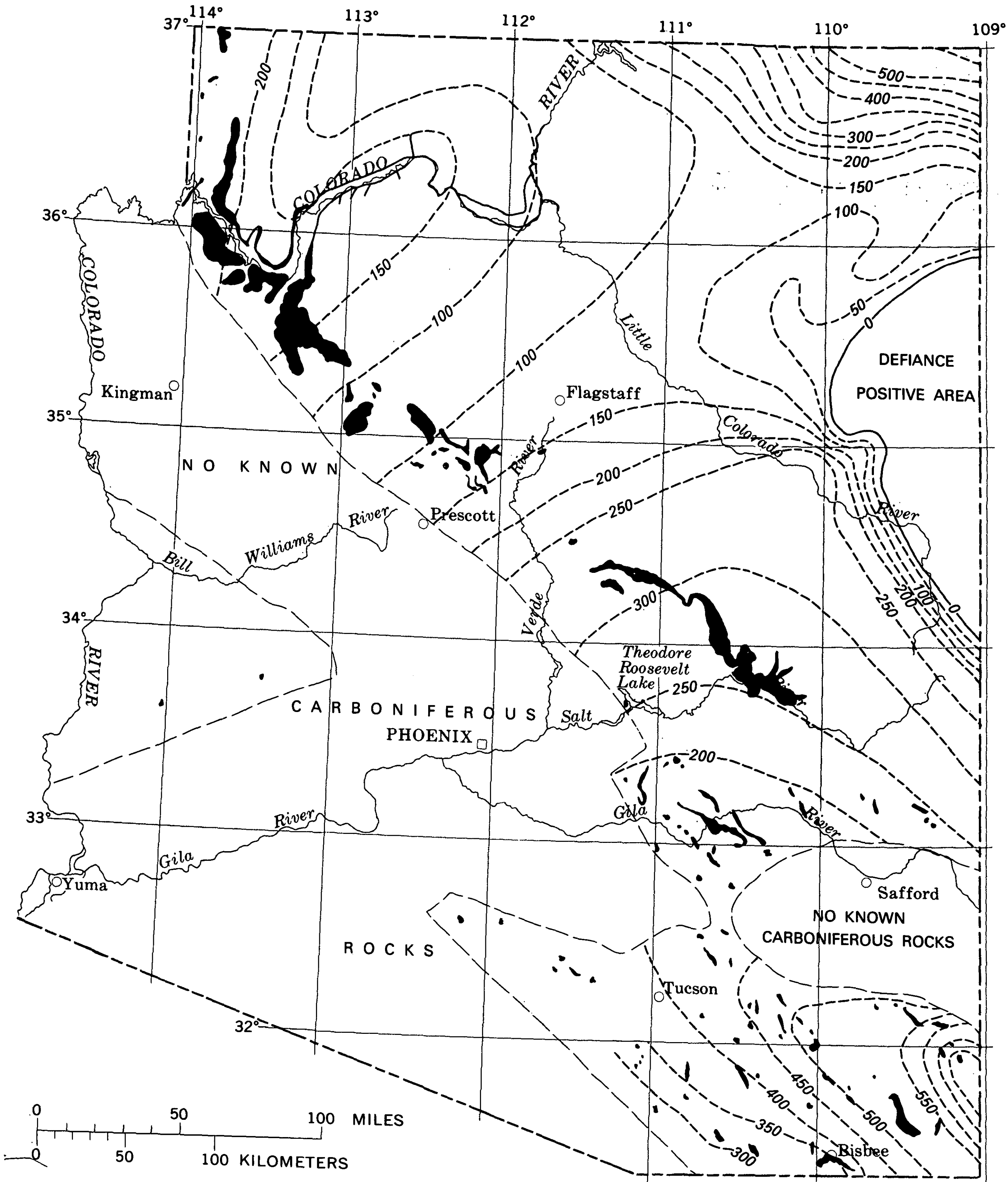

FIGURE 3.—Thickness (in meters) of Pennsylvanian rocks as inferred from present distribution.

known as: (1) Whitmore Wash, (2) Thunder Springs, (3) Mooney Falls, and (4) Horseshoe Mesa. Generally, these members are recognizable in subsurface drill tests as well as in outcrop.

The Redwall Limestone consists almost wholly of carbonate varieties and is generally free from insoluble residues, except chert. Granular carbonate rocks, especially crinoidal beds, predominate. Aphanitic limestone, dolomite, and chert are found in certain beds.

According to McKee (1969), the first transgression began in western Grand Canyon in late Kinderhookian time; the second, in Osagean time, was followed by regression in Meramecian time. Evidence of a third transgression is indicated by isolated remnants of Chesterian-age rocks preserved locally at the top of the Redwall Limestone. An unknown thickness of this formation was removed before initial deposition of the overlying Supai Group in Grand Canyon, the Naco Formation in central Arizona, and the Black Prince-Horquilla limestones of southern Arizona.

The Mississippian rocks of southern Arizona have not been studied regionally in any detail by any one worker. Effort has been concentrated largely in southeastern Arizona where the rocks of this system are thickest (fig. 2).

Thomas (1959) gave a brief summary of southeastern Mississippian highlights as then understood. Armstrong (1962) further defined lithologic and paleontological character found in extreme southeastern Arizona. He raised "Escabrosa" to group status and named two new formations: the Keating Formation below and the Hachita Formation above. Thus far, this terminology has not generally been used in southern Arizona because it does not appear to have regional application, especially to the west. Norby (1971) examined the conodont characteristics of eight widely distributed sections and provided additional lithologic detail.

All workers emphasize the granular crinoidal fragments of the Escabrosa Limestone. Some lithographic limestone, dolomite, chert, and oolitic units are also present. More acid-insoluble material seems to be near the base of the unit than is generally reported in the Grand Canyon country. This may be from the reworking of siliceous components of underlying Devonian strata.

The youngest representative of Mississippian strata in Arizona is found in extreme southeastern Arizona in the Chiricahua Mountains. It is known as the Paradise Formation and was first recognized by Stoyanow (1926, 1936). He described a 40-m-thick sequence assigned to the Paradise Formation as being both distinctive from, and above, the Escabrosa Limestone. This unit is thinner bedded and contains more siliceous components than does the Escabrosa Limestone, and is distinctly yellow where viewed from a distance. He considered it to be late Meramecian and early Chesterian in age. Norby (1971), on the basis of conodonts, considered the Paradise Formation to be late early Chesterian and the upper beds of the Escabrosa Limestone to be early late Meramecian in age. Armstrong (1962) noted that during Chesterian time the crustal instability, so well reflected in Pennsylvanian strata, was initiated. He referred to a paleogeographic feature in northern New Mexico and east-central Arizona as the Penasco dome. This same feature had earlier been referred to as the Defiance positive area (McKee, 1951), a name that seems firmly entrenched in contemporary literature dealing with the Arizona geologic framework. The evidence contained in the Paradise Formation, as pointed out by Armstrong, probably reflects instability of this more positive area and southerly withdrawal of Mississippian seas.

Norby (1971) assigned a late Kinderhookian age for the basal Escabrosa Limestone. Earlier, G. H. Girty (in Ransome, 1904) also had suggested that the lower Escabrosa Limestone is Kinderhookian in age.

The following comments about the depositional environments reflected in Mississippian strata of southern Arizona are taken from Norby (1971, p. 24), unless otherwise noted.

Mississippian strata, for the most part, were deposited in a warm shallow sea of normal salinity. Micritic limestone may represent isolation from currents, whereas oolitic and pelletoid limestones suggest intermittent currents related to wave and (or) tidal action. The crinoidal calcarenites that are very characteristic of the upper half of the formation suggest widespread stability of conditions suitable for the growth of crinoids. Also, this debris is well sorted, which suggests significant current activity, perhaps near or at wave base. The Paradise Formation, containing a variety of shale, sandstone, and carbonate, indicates fluctuations of sea level and near-shore environments. Armstrong (1962) noted that plant fossils in some of the shales are indicative of the proximity to land.

Norby suggested a rapid northwestward transgression in Kinderhookian time as well as a rapid regression in the late Meramecian. Seas reappeared in early Chesterian time, as indicated in the Paradise Formation. Apparently a second transgression during Osagean time, analogous to that recognized by McKee in the Grand Canyon region, has not been defined.

The relationship between Mississippian strata of the northern and the southern regions is not clear. In outcrop, near the geographical center of Arizona, a natural geographic basis is found for dividing these two domains. Stoyanow (1936), noting the thinning of Mississippian strata toward this region (fig. 2), as well as facies changes and local onlap of older Paleozoic strata, referred to the paleogeographic feature as Mazatzal land. Its original extent to the southwest is not known because of the general removal of Paleozoic rocks in that direction. However, on the basis of paleontological evidence, faunal intermingling may have been restricted; this restriction would indicate that a southwest-extending barrier may have existed. Figure 2 suggests that the thinning in central Arizona is related to activity on the Defiance positive area.

PENNSYLVANIAN

Pennsylvanian strata are thicker and more variable than Mississippian strata (fig. 3). They range in thickness from 0 to more than 725 m (2,370 ft) and include both continental and basinal deposits. McKee (1975b) gave an excellent discussion of statewide Pennsylvanian rocks. Ross (1973) provided a thorough discussion of Pennsylvanian depositional environments that prevailed in southern Arizona.

Although the early workers lumped Mississippian and Pennsylvanian strata together, it is now generally recognized that these two systems are separated by a hiatus that includes the extremes of each period. Evidence of exposure and solutioning of Mississippian carbonate rocks to produce a karstic surface is widespread. An insoluble chert rubble is present in many outcrop localities, and much of it has been reworked into basal Pennsylvanian beds. Red coloration of this zone is characteristic where not swept clean by erosion. The contrast between red beds at the base of Pennsylvanian strata and the clean light-colored carbonate rocks of the Mississippian strata makes an important marker horizon in wells drilled in northeastern Arizona.

The Pennsylvanian system contains more marine carbonate rocks in each corner of the State than in the center, except in the southwest, where there is no known record. In central-northern Arizona (much of the Plateau), the amount of carbonate rocks decreases and the amount of red-bed clastic rocks deficient in fossils increases; therefore, the upper limit of Pennsylvanian strata, for the most part, has not been effectively defined, especially in the subsurface. The clastic red beds of much of the Plateau region are lumped into the Supai Formation, which consists largely of Permian strata in east-central Arizona near the Plateau margin.

McKee (1975a) suggested a Pennsylvanian-Permian boundary in a part of the Grand Canyon, and Winters (1963) suggested a boundary in east-central Arizona. McKee recommended that the Supai be raised to group status and that new formations be recognized. Perhaps, as a result of further study, a method for establishing regionally correlatable units within the Supai Formation will be found. However, stratigraphic keys of regional extent will not be easily defined or accepted.

In each of the corners where Pennsylvanian marine carbonate rocks exist, a Permian boundary usually is described as occurring somewhere within a conformable stratal sequence. In central Arizona, along the Plateau edge escarpment, channel-fill and related deposits contain plant fossils that have yet to be studied. Regional stratigraphic considerations suggest that these plants are near the Pennsylvanian-Permian boundary, but on which side is not yet certain. Blazey (1971) did the initial work on plant forms from one fossiliferous locality.

The approximate thickness extremes of Pennsylvanian strata in the three corners, as recorded by McKee (1975b), are: northwest, 335 m (1,100 ft); northeast, 550 m (1,800 ft); and southeast, 730 m (2,400 ft). Pennsylvanian strata are absent beneath Permian rocks on the Defiance positive area, and, in the center of the State where clastic rocks prevail, they are 90–180 m (300–600 ft) thick (fig. 3).

The northwestern area probably contains the eastern marine edge of the Cordilleran geosyncline. The northeastern region is the edge of the Pennsylvanian Paradox basin of southeastern Utah and southwestern Colorado. The marine rocks of the southeastern region, the thickest of Pennsylvanian age in Arizona, are considered a part of the Sonoran geosyncline. This relatively thick sequence in southeastern Arizona and New Mexico originally accumulated in what frequently is called the Pedregosa basin (Kottlowski, 1960). Kottlowski provided an excellent summary of the Pennsylvanian stratigraphy of the southern Arizona region.

The recognition of three different marine sections, separated by a red-bed clastic section in the northern region, has led to four different sets of nomenclature. Neither the eastern Nevada nor the southern Utah sections is reviewed here.

NORTHERN REGION

The marine section of eastern Nevada thins into northwestern Arizona, where red beds assigned to the Supai Formation dominate. McKee (1969, p. 88) suggested that the top of the Pennsylvanian System is marked by a distinctive limestone-siltstone pebble conglomerate "throughout Grand Canyon." Using this reference surface, McKee (1975a) elevated the Supai to group status and defined three new formations. He also raised the Permian Esplanade Sandstone from member to formational rank. The newly delineated Pennsylvanian units, from oldest to youngest, are: (1) Watahomigi Formation, (2) Manakacha Formation, and (3) Wescogame Formation. The last is overlain by the conglomerate thought to be Wolfcampian in age. The type sections for these units are in Havasu Canyon.

The Watahomigi Formation unconformably overlies the Mississippian Redwall Limestone, is 65 m thick, contains largely limestone and mudstone in about equal parts, and is thought by McKee to be Morrowan and Atokan in age. The overlying Manakacha Formation is 77 m thick, consists of sandstone and minor mudstone, and is either Atokan or Desmoinesian in age. The Wescogame Formation is 61 m thick, consists largely of massive crossbedded sandstone or sandy limestone, is probably of Virgilian age, and contains a basal conglomerate. Overlying the Wescogame Formation is the basal conglomerate of the Permian Esplande Sandstone, a prominent cliff-forming sandstone in Grand Canyon. Noble (1922) had divided the Supai Formation into three members lettered A, B, C from top to bottom. His measured section at Bass Canyon includes a conglomerate high in member B that probably is the conglomerate marker of McKee.

East of Grand Canyon, Carboniferous rocks do not again crop out in Arizona. In the subsurface, these rocks are the prime objective in petroleum exploration in the Four Corners region. The nomenclature for Pennsylvanian strata in this region seems to be in a state of flux. In Utah (see chapter on Utah), Pennsylvanian rocks are thickest in the subsurface. They change facies and thin to the southwest in northeastern Arizona. The change southwestward is to undifferentiated red beds of the Supai Formation.

CENTRAL REGION

Pennsylvanian rocks are exposed in canyons and cliffs associated with the southern edge of the Plateau—the Mogollon Rim escarpment (fig. 1). The exposure of Mississippian-Pennsylvanian(?) rocks to the south is in the walls of Oak Creek Canyon about 161 km (100 mi) from Grand Canyon. Stratigraphic differences between the Grand Canyon to the north and the main Mogollon Rim segment farther south and east emphasize the stratigraphic importance of the Oak Creek Canyon locality. No recognized diagnostic fossils are above Mississippian exposures; correlations must be based on lithology. Whereas McKee's Supai Group in Grand Canyon (Havasu Canyon) is about 335 m (1,100 ft) thick, 204 m of which is Pennsylvanian, the Supai Formation in Oak Creek Canyon is nearly 780 m (1,600 ft) thick (Twenter and Metzger, 1963). It is readily divisible into three principal lithologic units: upper, middle, and lower, or A, B, and C, respectively. Although fossils are absent, the Supai Formation generally has been considered Pennsylvanian-Permian in age. Limestone-siltstone pebble conglomerates in the middle (B) slope-forming unit (84 m thick) might possibly bear a significant relationship to the Pennsylvanian conglomerates of McKee at Grand Canyon. If so, then the lower 122–183 m (400-600 ft) of the Supai Formation could be Pennsylvanian in age; thickness of the Pennsylvanian rocks in the Supai Group at Grand Canyon is similar. This lowest part contrasts with the remaining Supai in that it forms cliffs and, in addition, certain beds contain vertically and horizontally oriented tubular chert phenomena.

Forty-eight km (30 mi) farther south is Fossil Creek Canyon, an important stratigraphic reference point at the west-northwest end of the main Mogollon Rim of central Arizona. Along or beneath the rim, Carboniferous rocks are variably exposed for 160 km (100 mi). At Fossil Creek, the stratigraphic section above the Mississippian limestone contains some fossiliferous limestone in the lowest 76 m (250 ft); the fossils are probably of Demoinesian age (Huddle and Dobrovolny, 1945). These rocks, combined with the Supai Formation, total about 550 m (1,800 ft) in thickness. Again, there is no fully accepted Pennsylvanian-Permian boundary. However, beneath a conglomerate about 244 m (800 ft) above the top of the Mississippian, is a coaly zone from which spore-pollen has been recovered and examined. Several years ago I submitted a sample from this zone to Norman O. Frederiksen, then of the Socony Mobil Oil Co. He reported that the materials were probably lower Wolfcampian (Hueco) but that they could be as old as Upper Cisco (Virgilian). This coaly zone (this and the overlying conglomerate were first reported by Ransome in 1916; Noble, in 1922, while discussing a Supai conglomerate in Grand Canyon, referred to Ransome's Supai conglomerate at Fossil Creek) and its stratigraphic setting, have been discussed by Peirce and others (1977). The zone is within a stratigraphic interval about 152 m (500 ft) thick that contains interbedded limestone-siltstone pebble conglomerates, the lowest of which is about 76 m (250 ft) below the coaly bed. This lowest conglomerate, in turn, is about 135 m (450 ft) above the limestone that contains Desmoinesian fossils. It seems possible, therefore, that the 213-m (700-ft) interval between the Desmoinesian limestone and the possible lower Wolfcampian coaly zone includes all Missourian and either all or part of Virgilian time.

Lithologic correlations can probably be made between Oak Creek Canyon and Fossil Creek Canyon even though the latter section is thicker. Except for the fossiliferous limestone near the base of the Fossil Creek section, the sections appear analogous although not identical. A threefold division seems reasonable at both localities, the conglomerates falling into the middle or B unit. Most likely the B unit contains the Pennsylvanian-Permian boundary in both locations. Brew (1965) suggested that the Pennsylvanian strata of central Arizona are no older than Desmoinesian. If Brew is correct in his age assignment, then the Watahomigi (Morrowan) of McKee in Grand Canyon is not represented in central Arizona sections. Because of the Atokan and (or) Desmoinesian age range assigned to the Manakacha, it may or may not be represented in central Arizona. However, the Wescogame of "probable" Virgilian age, which has a basal conglomerate, could have representation in the middle, or B, unit. A time and lithostratigraphic correlation with the Permian Esplanade Sandstone, and its Wolfcampian basal conglomerate, theoretically could fall within the A unit (largely sandstone) of Oak Creek Canyon.

McKee's data indicate that Missourian time in the Grand Canyon region is represented by an hiatus. Brew suggested that the conglomerate-bearing unit (middle, or B) in central Arizona is Missourian in age. This is a projection from 80 km to the east and is not supported by actual paleontological data in or near Fossil Creek. I suggest that the data from the coaly bed limit the amount of section, if any, that should be assigned to the Missourian. The conglomerates represent erosional hiatuses in which unknown quantities of section were removed. At present, it seems more appropriate to consider them a part of a section that is probably Virgilian-Wolfcampian rather than Missourian. On this basis, the Missourian hiatus postulated by McKee in Grand Canyon may extend, at least in part, to the Oak Creek and Fossil Creek localities.

If correlation with the Grand Canyon section of McKee is attempted, the following possibilities should be considered: Watahomigi—not represented; Manakacha—lower, or C; Wescogame—middle, or B; Esplanade Sandstone—upper, or A and, possibly, part of middle, or B.

The Pennsylvanian strata of central Arizona, including the subsurface, are referred to the Pennsylvanian-Permian Supai Formation, the Naco Formation of Pennsylvanian age, or both. The Naco Formation was defined in southern Arizona and originally included Permian rocks. Whereas the southern Arizona section now includes a Naco Group, a Naco Formation is still used in central Arizona in both the northern part of the Basin and Range province and the southern Plateau province.

Eastward and southward from Fossil Creek, the thickness of sections containing non-red Pennsylvanian age strata increases. The thickness of the non-red section, dominated by limestone and gray shale, increases from a few meters at Fossil Creek to more than 370 m in the Carrizo Creek-Salt River Canyon area 130 km distant. Although this change usually is described as gradual throughout this distance, a significant change occurs across a zone near Canyon Creek, only 48 km from the Carrizo Creek-Salt River region (Peirce and others, 1977). The contrast in sections at the extremes, that is, Oak Creek to the north and the Salt River Canyon region to the south, traditionally has been explained as a northwesterly gradation to Supai Formation as if there were meter-by-meter replacement. Using the top of the Mississippian limestone (Redwall) and the bottom of the Permian Fort Apache Member of the Supai Formation as marker horizons, we find that this Pennsylvanian-Permian interval in the Carrizo-Salt River area is 610 m (2,000 ft) thick. At Fossil Creek, the thickness is 503 m (1650 ft) and at Oak Creek Canyon, about 380 m (1,250 ft). Most of this thinning appears to be in rocks of Pennsylvanian age. In addition to the simple thinning, a lateral facies change is represented by loss of limestone west of Canyon Creek. These changes are found beneath the lowest bed in which conglomerates appear all across the region. The presence of Desmoinesian fauna in a thin marine limestone near the base of the Pennsylvanian section at Fossil Creek, coupled with a Desmoinesian through Virgilian marine fauna at Garrizo-Salt River, suggests an offlap relationship. This helps to explain the contrasts in both thickness and facies that are seen mostly within Pennsylvanian rocks. In central Arizona, these changes might be explained more naturally by a waning Naco Formation history than by the onset of a contrasting complex Supai depositional history.

Brew (1965) studied the stratigraphy of the Naco Formation in outcrop along the Mogollon Rim southeastward to the point where Paleozoic rocks pass beneath the volcanic rocks of the White Mountain region. He divided this formation into Alpha, Beta, and Gamma members from the base upward. The Alpha Member, representing the red clastic zone related to the karstic surface that is extensive above the Redwall Limestone in this region (Huddle and Dobrovolny, 1952), ranges from 12 to 27 m in thickness. The Beta Member makes up most of the Naco Formation in the rim region. The thickest complete section of Beta Member measured by Brew is 210 m. The member may be about 256 m thick in the southeast where complete continuous sections are not known. Brew (1965, p. 50) wrote: ——"the member is a richly fossiliferous succession of ledge-forming gray, brownish-gray, and olive gray limestone with interspersed intervals of slope-forming calcareous shale, shaly mudstone, mudstone, and less common siltstone * * * *."

According to Brew, the most complete depositional record preserved in the Beta Member is to the southeast. He suggested that a cliff-making section 55 m thick near Black River but not present to the northwest, probably represents the northernmost extension of the typical Pennsylvanian Horquilla Limestone, the oldest formation of the Naco Group (Gilluly and others, 1954) of southeast Arizona. At Black River, this Horquilla-like part of the Naco section is indicated by Brew to be middle and upper Desmoinesian in age.

Brew (1965, p. 57) made the following observation of the higher Missourian part of the Beta Member at Black River: "—one horizon contains a lenticular bed of conglomerate with red quartzite pebbles and quartz sand in the matrix. The source area of the quartzite is as yet undetermined, but the presence of this bed clearly indicates a departure from the prevailing marine conditions."

The highest member of the Naco Formation of Brew in this central Arizona region is the Gamma Member. It is, in parts of the region, readily distinguished from the underlying Beta Member because of the presence of more red and brown clastic rocks and less limestone, which leads to longer slopes. Brew suggested that this unit is a transition between the marine conditions of the Naco Formation and the nonmarine conditions of the lower Supai Formation and that it ranges in thickness from 21 m at Fossil Creek Canyon, the northwesternmost locality, to about 91 m toward the southeast. Brew stated that this member is difficult to define objectively in the northwestern sections because fossiliferous limestone is absent, red beds of the Naco Formation are present below the member, and red beds of the Supai Formation are above. Brew noted, but did not emphasize, conglomerates to the southeast in the Gamma Member. It seems surprising that at Fossil Creek Canyon he drew an upper boundary of the Gamma—therefore, the top of the Naco Formation—below the entire section that contains conglomerates, the best exposed set of conglomerates along the rim. He also suggested that the lower contact of the Gamma Member is time-transgressive, being older to the west and younger to the east. More specifically, he visualized this contact to the east to be very latest Pennsylvanian in age (possibly even lowest Permian) and Desmoinesian at Fossil Creek to the west. I think that the conglomerate and floral data previously mentioned may have significant correlative value. At Fossil Creek, the coaly unit (not recognized by Brew), probably either latest Virgilian or earliest Wolfcampian in age, is estimated to be approximately 76 m above Brew's Gamma Member top in what he calls Supai Formation of Missourian age. Brew's age designations and definitions of a Gamma Member at Fossil Creek, as he himself hints, are probably subject to revision.

As pointed out, Brew's attention was attracted to a conglomerate in his Missourian (Beta) section to the southeast because it contained quartzite clasts and quartz sand. He described "intraformational" conglomerates in several sections of the Gamma Member. In a later study, Peirce and others (1977) recognized Gamma Member conglomerates that contain large feldspar and quartz grits, as well as quartzite, chert, and calcarenite clasts. These are not "intraformational" conglomerates. They are evidence of tectonic activity along the Defiance positive area that was to the east and northeast. They are not directly related to a Supai Formation delta prograding towards the southeast, Brew's explanation for the seeming younging of the Gamma Member to the southeast. More likely, transgressive-regressive cycles, responsive to regional tectonic or climatic activity, are the major cause for the shallow-water to subaerial environments that alternate vertically. That land areas supporting lush vegetation existed from time to time is suggested by plant fossils and carbonaceous zones that are closely related to conglomerates. In the transition phase (Gamma Member) of Brew, little evidence is seen of deposition in a classic deltaic environment, which is frequently invoked to explain Supai Formation-Naco Formation relationships. The hiatuses are probably longer than usually is recognized. Havenor (*in* Kottlowski and Havenor, 1962, p. 79) is credited with suggesting: "—that deltaic beds are only a minor part of the Supai sequence, believing that the lower Supai red beds and carbonate rocks (Gamma Member of Brew) are predominately shallow-water marine deposits laid down in a shallow ephemeral sea—where a lowering of sea level by only a few feet may have exposed several hundred square miles of the sea bottom."

The entire Naco Formation in the Mogollon Rim outcrop region is as much as 360 m (1,180 ft) thick in the eastern region. To the west, both in outcrop and in the subsurface, it thins and changes to strata referred to the Supai Formation. To the east in the subsurface, it may thicken before it rather abruptly wedges against the Precambrian rocks of the Defiance positive area paleogeographic feature. The environments that prevailed along the interface of the Naco seaway and the positive area in which sand-producing granite was exposed are not known and have not been tested by drilling. The subsurface onlap and pinchout of Pennsylvanian strata to the northeast has been discussed by Lokke (1962) and Peirce (1970; 1976; 1977).

To the south, but still in central Arizona, isolated exposures of Pennsylvanian strata are found in various mountain ranges where they are everywhere truncated beneath Cretaceous (Clifton-Morenci, Deer Creek, Christmas) or Tertiary (Superior, Mescal Mountains, and so forth) rocks.

Although the name Naco Formation is used in the Mogollon Rim region, the Naco Limestone of Stoyanow (1936) is in use farther south to describe Pennsylvanian rocks. However, still farther south, where Permian marine strata overlie Pennsylvanian strata, the nomenclature is again changed, and the names Black Prince Limestone, Horquilla Limestone, and Earp Formation are used to describe the Pennsylvanian and Pennsylvanian-Permian section.

Occasionally, attempts are made to carry or extend the southern terminology northward. Recall that Brew noted a possible representative of the Horquilla Limestone at Black River. Also, the transitional aspect of the Gamma Member is analogous in some ways to the Earp Formation farther south (Ross, 1973). The thickest of the partial Pennsylvanian sections approximates 427 m (1,400 ft) at Coolidge Dam to the east and at Superior to the west. Kottlowski and Havenor (1962) noted that, although limestone and siliciclastic rocks are present in about equal amounts at Superior, the limestone at the Coolidge Dam locality is more abundant. This west-to-east increase in limestone may bear a direct relationship to the west-to-east increase in limestone along the rim 100 km to the north. This implies a lithologic variance trend that would lie in the northeast-southwest quadrants. Evidence, which is pointed out later, suggests that such a trend might well have extended into southwestern Arizona.

SOUTHEASTERN REGION

In southeastern Arizona, Pennsylvanian as well as Permian strata are contained within the Naco Group. Units now considered to be Pennsylvanian in age are the basal Black Prince Limestone and overlying Horquilla Limestone. The Earp Formation overlies the latter and is believed to contain an undefined Pennsylvanian-Permian boundary.

The Black Prince Limestone was named by Gilluly and others (1954) and originally was considered Mississippian in age, but a Pennsylvanian age is not totally discounted. Although thinner, the base of the Black Prince in several sections appears analogous to the Alpha Member of the Naco Formation of Brew to the north. The similarity is derived from the erosion (solution) of the underlying cherty carbonate rocks of the Mississippian Escabrosa Limestone and the production of red beds and associated, often reworked, residual chert. The unit, ranging in thickness from 36 to 85 m, contains limestones not unlike the Escabrosa and Horquilla Limestones. Later, Nations (1963) concluded that this formation is lowermost Pennsylvanian (Morrowan) in age, and that the Mississippian fossils were reworked from below. The Black Prince Limestone is not everywhere recognized in southeastern Arizona; where it is absent, the Horquilla Limestone (Naco limestone as restricted by Stoyanow) overlies the Mississippian Escabrosa Limestone or, in extreme southeastern Arizona, the Paradise Formation.

The Horquilla Limestone ranges from 305 to 400 m (1,000 to 1,600 ft) in thickness and contains some beds of red and green mudstone that impart a topographic character of steep slopes containing many ledges. The Horquilla Limestone is more abundantly fossiliferous than the underlying Mississippian strata and contains fusulinids, which the latter does not (Bryant, 1968). Most of the Pennsylvanian strata in southern Arizona are contained in the Horquilla Limestone, and most of the Pennsylvanian section of Brew is contained in the Beta Member of the Naco Formation.

Ross (1973) did a detailed study of the Pennsylvanian and early Permian depositional history of southeastern Arizona. He included the Mogollon Rim region as far west as Fossil Creek Canyon. Although this work is much too detailed to be included here, the regional integration accomplished is commendable. Among his conclusions are: (1) the Black Prince Limestone is recognizable as far northwest as the Superior section, (2) the conglomerate-bearing section at Fossil Creek contains the Pennsylvanian-Permian boundary, (3) the Naco Formation of Brew in central Arizona can be treated as the Horquilla Limestone and Earp Formation, and (4) depositional history is complex and involves concurrent faulting as well as many hiatuses.

The westernmost exposure of Pennsylvanian strata of the southeastern type occurs in the Vekol Mountains in the southwestern corner of Pinal County. Ross (1973) suggested that the remaining 183 m (600 ft) of limestone represents the lower part of the Horquilla Limestone and that the section consists of about 80 percent carbonate rocks, a percentage known elsewhere only in extreme southeastern Arizona. About 161 km (100 mi) to the northwest, in the Harquahala Mountains, Varga (1977, p. 6) reported that Supai Formation was found above Redwall Limestone. He described the Supai Formation as consisting dominantly of "quartzite interbedded with minor limestone and phyllite layers," the section, though folded and metamorphosed, approximating 365 m (1,200 ft) in thickness.

The contrast between the Vekol and Harquahala sections demands explanation, whether forthcoming or not. These sections might not now have the same geographic relationships, one to the other, as when originally deposited. However, a northeast-trending line between the Supai and Naco formations in central Arizona can be projected between these sections. Perhaps a regional major northeast depositional strike is involved that could bear some relationship to Stoyanow's "Mazatzal land" trend.

GENERAL PALEONTOLOGY

The following remarks are directed more toward the contributions to stratigraphic understanding made through paleontological study than to a listing of fossils.

The paleontology of Arizona Carboniferous rocks has not been exhaustively treated in any single published work. Whereas the Grand Canyon and Mogollon Rim of northern Arizona offer outcrop continuity, the Basin and Range province of southern Arizona presents a disconcerting discontinuity, and a plethora of local studies is the result. Only some very general highlights are offered here.

Most of the fossils attributed to the Arizona Carboniferous lived in marine environments. Although plant remains are relatively scarce, they may offer hope for making progress on the Pennsylvanian-Permian boundary question in central Arizona. The recognition of an extensive plant-fossil community in that region is such a new development that opportunities for original research still remain. Peirce and others (1977, p. 49) noted an unidentifiable bone fragment in a conglomerate from the Gamma Member of the Naco Formation of Brew (1965), thus hinting at another potential source of historical information.

The volume of paleontological literature seems to be weighted in favor of Pennsylvanian rocks, where Fusulinacea offer a special attraction. However, this and the study of microfossils is a late development because the earlier workers focused attention on the megafossil groups. Today, research effort seems to be directed to the study of conodonts as a possible means for refined zonation.

The earliest reference to Carboniferous strata in northern Arizona is attributed to Marcou (1856). Gilbert (1875) suspected that certain fossils in Grand Canyon represented "Lower Carboniferous" and other fossils, a "Coal Measures" fauna. Darton (1925) presented the first general summary of Arizona geology and included a section on the "Carboniferous System," where Carboniferous fossils are listed. Early studies clearly show that the general zonation of Mississippian strata was well outlined in the early 1900's.

MISSISSIPPIAN

Much of the pioneer paleontological work was done by scientists of the U.S. Geological Survey. G. H. Girty, in particular, studied many of the collections made by the eminent early field geologists such as N. H. Darton and F. L. Ransome. It was

Girty, as reported in Ransome (1904), who recognized Mississippian and Pennsylvanian fossils in the Bisbee quadrangle. In Girty's opinion, both Kinderhookian and Osagean time were represented, but Chesterian time was not. Furthermore, he thought that certain forms represented a slightly younger age than Osagean. These conclusions have not been seriously changed by subsequent research.

The absence of Chesterian strata in southern Arizona, except in the Chiricahua Mountains (Paradise Formation), now is recognized throughout the Basin and Range province wherever Mississippian rocks have been studied. Girty's deductions appear to have stemmed largely from his knowledge of brachiopods.

Stoyanow (1926, 1936) briefly reviewed Paleozoic correlations in Arizona by using paleontology as a major tool. He emphasized the paleontological separation of Mississippian and Pennsylvanian limestones where they had been lumped together as a map unit. He recognized that Carboniferous geologic history could not properly be unraveled until the two systems were mapped separately. He extended to central Arizona the region in which upper Mississippian strata are absent. At the same time, he defined the upper Mississippian Paradise Formation in the Chiricahua Mountains of extreme southeastern Arizona, recognizing these strata as being late Meramecian and early Chesterian in age. Stoyanow apparently used crinoids, brachiopods, and bryozoans to advantage.

At the time of Stoyanow's writing (1936), the fossils of the Grand Canyon Redwall Limestone had not been studied in any detail. However, a section of Redwall Limestone at Jerome, on the Grand Canyon side of Stoyanow's Mazatzal land, had been studied by C. E. Wooddell (1927), a Stoyanow student. From this work, Stoyanow noted forms in the Redwall Limestone not present in the Escabrosa Limestone and vice versa (at a much later date, Sando (1964) was to study corals of the Redwall Limestone and draw a similar conclusion). Stoyanow (1936) also said that the Redwall Limestone section at Jerome was late Kinderhookian and Osagean in age, a conclusion that apparently remains valid.

McKee and Gutschick (1969) collected extensively from the Redwall Limestone of the Plateau region. Their collections contain 17 animal groups and 1 plant group. Many of these groups were studied extensively by specialists, and the results were reported by McKee and Gutschick (1969).

Elsewhere, McKee (1969) wrote that the larger Redwall fossil groups are in distinctive associations, the most important being the coral-brachiopod-crinoid, foraminifer-brachiopod, and brachiopod-bryozoan. Many of the Redwall fossils are either local or long ranging, and thus of little stratigraphic value. However, the foraminifers, brachiopods, and corals are useful zone indicators.

According to Betty Skipp (*in* McKee and Gutschick, 1969, p. 173–256), the foraminiferal succession in the Redwall Limestone ranges from late Kinderhookian to middle Meramecian in age. McKee and Gutschick, referring to brachiopod studies then in progress by J. T. Dutro, Jr., said that these forms range in age from late Kinderhookian into Meramecian, and that Chesterian is represented in one section at Bright Angel Trail. In summarizing paleontological studies, these workers concluded that all other fossil groups represent lesser parts of the stratigraphic section and are of ages between the extremes indicated.

W. J. Sando (also *in* McKee and Gutschick, 1969, p. 257–343) provided an interesting discussion of corals. Among other things, he suggested that the Redwall Limestone is linked more closely to the Madison Group of the northern Cordilleran region than to the Escabrosa Limestone of the southern region.

Some preliminary conodont studies by students at Arizona State University (Norby, 1971; Racey, 1974; Walter, 1976) suggest that detailed conodont work might assist in determining close zonation of Mississipian rocks. Norby recorded a more complete conodont zonation for the Escabrosa Limestone of southern Arizona than did Racey in central Arizona, or Walter to the northwest in Redwall country. Currently, W. J. Purves, a University of Arizona doctoral candidate, is making a comprehensive study of the Mississippian of Arizona with emphasis on conodont zonation and detailed carbonate petrology.

PENNSYLVANIAN

The recognition of Pennsylvanian fossils, quite naturally, was contemporaneous with the studies that led to the recognition of juxtaposed Mississippian forms. Noble (1922) pointed out that it was F. B. Meek who identified Pennsylvanian forms for Gilbert (1875) in western Grand Canyon in beds that Noble later correlated with the lowest unit of Noble's redefined Supai Formation (C) and that McKee (1975a) called the Watahomigi Formation. Although McKee stated that Pennsylvanian fossils bear direct relationships to conglomerate beds, his type section descriptions do not reflect the presence of fossils. McKee (1975b, p. 297) later said: "The discovery * * * of invertebrate fossils, including fusulinids and brachiopods, extensively distributed in the Grand Canyon region throughout the rocks called Supai has greatly clarified the age relations of various rock units in that formation * * *" We hope that future clarification of this statement will shed additional light on the specific fossil localities that for so long have escaped the attention of many geologists.

Darton (1925) cited many lists of fossils collected from various localities within the Basin and Range province that were identified, largely by G. H. Girty, as Pennsylvanian. Girty's studies also led to the recognition that strata lumped into Ransome's (1904) original Naco limestone contained Permian (Hueco) forms.

Gilluly, Cooper, and Williams (1954) raised the Naco to group status and differentiated six formations in central Cochise County. Their Pennsylvanian representatives were the Horquilla Limestone (Atokan to mid-Virgilian?) and Earp Formation (Virgilian and basal Wolfcampian). Nations (1963) determined that the Black Prince Limestone beneath the Horquilla Limestone also is Pennsylvanian in age (Morrowan). Bryant (1955) gave considerable attention to the Earp Formation, and Rea and Bryant (1968) discussed an important marker conglomerate within the Earp Formation.

Both Winters (1963) and Brew (1965) provided essential paleontological data relevant to Pennsylvanian stratigraphy in the Mogollon Rim region. Lokke (1962) provided a surface to subsurface correlation of Pennsylvanian strata along the southern edge of the plateau. He said that fossiliferous surface rocks tend to change to an unfossiliferous redbed sequence northward, and this change complicates dating and correlation of strata northward. He emphasized this point by noting that whereas 32 fusulinid-bearing intervals were recognized in the surface section (Salt River-Carrizo area), only one interval was observed in the subsurface about 70 km to the north. Fortunately, this one interval afforded a time horizon that enabled him to conclude that, northward (p. 85) : "* * * significant thinning of Pennsylvanian sediments must be recognized in addition to the previously described (by other workers) interfingering of red clastics with Naco subsurface equivalents."

Blazey (1971) investigated a plant fossil locality in a newly opened uranium prospect (Peirce and others, 1977) under Promontory Butte along the rim, and studied both macrofossils and microfossils. He identified 21 species in 18 genera of macrofossils, and 41 species in 29 genera of microfossils. This is a significant locality because it is within a sequence of "Supai Formation" clastic rocks that otherwise are not fossiliferous. According to Blazey (p. 30) :

> The floral composition, although not unusual, has two rather striking features in contrast to other floras of late Paleozoic age. These are: (1) the complete lack of lycopsids, which are almost always associated with form genera of sphenopsids and pteridophylls, and (2) the association of younger typically Permian types with older typically Pennsylvanian types. Together these features present a transitional character to the floral composition.

Blazey concluded that the plant zone is near the Pennsylvanian-Permian boundary, and he seemed to thin that it was probably Permian (Wolfcampian). This zone probably correlates with the coaly bed at Fossil Creek 40 km to the west.

Brew (1965) described his Gamma Member of the Naco Formation at Carrizo Creek as "Post-Virgilian," but not Wolfcampian, in age. One wonders if both these workers saw transitional floras and faunas. Peirce and others (1977), on the basis of conglomerates, correlated these two zones. The Promontory Butte locality does not contain the limestone that is present at sections to the east, but this difference is attributed to lateral changes influenced by mild tectonic activity west of Canyon Creek.

Ross (1973) reported the results of the most detailed stratigraphic zonation of Pennsylvanian strata ever undertaken in the Arizona Basin and Range province, including the Mogollon Rim as far west as Fossil Creek Canyon. This work is an excellent example of the kind of stratigraphic detail that is made possible by meticulous paleontological zonation. In this study, stratigraphic refinement evolved, in large part, from the study of fusulinids. However, in the absence of fossil data, especially westward along the Mogollon Rim, geologists must make subjective decisions, and I think that Ross' correlations at Fossil Creek should seriously be questioned.

Whereas Pennsylvanian seas made few inroads into the northwestern and northeastern corners of Arizona, they transgressed extensively in the southeastern corner. Ross depicts northwesterly transgression and divides the depositional framework into basinal and flanking-shelf facies. Pennsylvanian marine strata of Desmoinesian age extended as far north as Fossil Creek in central Arizona. However, the seas here were ephemeral and regressed south and east for the remainder of Pennsylvanian time. True basinal facies formed only in the Pedregosa basin of extreme southeastern Arizona where, according to Ross, the combined Pennsylvanian-lower Permian sequence attains a maximum thickness of

TABLE 1.—*Principal users of Carboniferous rocks and products in 1977*

Location (Number shown in fig. 1)	Producer (Jan. 1, 1978)	Formation source, products, and facilities
	Apache County	
Field (oil and minor gas)		
1. Teec Nos Pos, Navajo Indian Reservation.	Energy Reserves Group	Pennsylvanian Paradox Formation; 3 wells.
2. East Boundary Butte, Navajo Indian Reservation.	Merrion and Bayless	Pennsylvanian Paradox Formation; 4 wells.
3. Dry Mesa, Navajo Indian Reservation.	Monsanto Co	Mississippian Redwall Limestone; 3 wells.
4. Dineh-bi-Keyah, Navajo Indian Reservation.	Kerr-McGee Corp	Igneous sill in Pennsylvanian Paradox Formation; 18 wells.
Total oil production 1954–77	16.2 million barrels	
	Yavapai County	
Cave (commercial)		
5. Highway 66, Grand Canyon Caverns.		In: Mississippian Redwall Limestone.
Limestone products		
6. Nelson siding, Santa Fe Railroad.	U.S. Lime Division, The Flintkote Co.	Mississippian Redwall Limestone; quarry and kilns; lime products.
7. Clarkdale	Amcord, Inc., Phoenix Cement Co.	Mississippian Redwall Limestone; quarry and plant; cement.
	Gila County	
8. Near Miami	Inspiration Consolidated Copper Co.	Mississippian Escabrosa Limestone; quarry; metallurgical flux and lime for copper processing.
	Greenlee County	
9. Morenci	Phelps Dodge Corp	Mississippian Modoc Limestone; quarry; metallurgical flux and lime for copper processing.
	Pinal County	
10. Hayden	(1) McFarland-Hullinger for ASARCO; (2) Kennecott Copper Corp.	Mississippian Escabrosa Limestone; 2 mills and smelters; 2 quarries; metallurgical flux and lime for copper processing.
11. 6 miles southeast of San Manuel	Magma Copper Corp	Pennsylvanian Horquilla Limestone; quarry; metallurgical flux and lime for copper processing.
	Pima County	
12. Rillito	Arizona Portland Cement Co., Div. Calif. Portland Cement Co.	Mississippian Redwall Limestone and Pennsylvanian Horquilla Limestone; quarry and plant; cement.
13. North end Santa Rita Mountains	Andrada Marble Co.	Mississippian Escabrosa Limestone (marble); roofing granules, feed additive, landscaping.

Total Carboniferous quarried (1976): estimated 2.5 million short tons.
Quicklime and cement produced (1976): estimated 1.2 million short tons.
Value of quicklime and cement produced (1976): estimated $42 million.

about 1,800 m (6,000 ft). According to Ross, faulting during Pennsylvanian time influenced lithofacies distribution.

UTILIZATION OF CARBONIFEROUS ROCKS

Carboniferous rocks in Arizona are used both directly (materials quarried and processed) and indirectly (commercialized caverns; sources of petroleum). Table 1 presents a summary of principal exploitation sites, producers, uses, and some quantitative estimates of production and value. We estimate that the value level for all uses of Carboniferous rocks in Arizona has reached $50 million per year. Cement and quicklime are the two major products sold in interstate commerce, constituting about 80 percent of this estimated total dollar value. Much of the remainder is produced by internal operations managed by copper producers in connection with the processing of copper ores and concentrates, principally lime for pH control in mill flotation circuits and as limestone flux in smelters. Use in acid neutralization may increase in the future. The varied uses of limestone and additional data about limestone in Arizona have been discussed by Keith (1969).

The prime contributors to the limestone-derived products in Arizona are the two Mississippian carbonate units. The Redwall Limestone in and near the Plateau province supports two major limestone products operations (Nos. 6 and 7 in fig. 1 and table 1), and the Escabrosa Limestone in the Basin and Range province supports one large cement plant west of Tucson (no. 12).

Petroleum production in Arizona is miniscule, amounting to slightly more than 16 million barrels since the first discovery in 1954. Most of this has been produced since 1967 when the largest field, Dineh-bi-Keyah (Navajo for "The People's Field"), was discovered. Although much of the petroleum production in the Four Corners region is closely related to Carboniferous (Pennsylvanian) rocks, the reservoir at Dineh-bi-Keyah is an igneous sill in Pennsylvanian strata. The sill is believed to be early Tertiary in age and occupies the crestal part of an anticlinal structure. In general, the petroleum potential in northern Arizona is limited by the large region of thin nonmarine Pennsylvanian strata (fig. 3). Although petroleum occurrences of significance are not known in southern Arizona, effort is being made to evaluate deep structural attributes in that area.

A solution cave, such as the well-patronized Grand Canyon Caverns (no. 5) west of Flagstaff on busy Route 66, is an example of indirect usage. This cave extends downward from the present surface, which happens to be the exhumed Redwall Limestone-Supai Formation contact. The present cave may be related to the karst surface that formed in Late Mississippian-Early Pennsylvanian time. The cave seems devoid of speleothems and therefore appears inactive. Perhaps the original dissolving action is a Paleozoic feature, and the more recent history has been devoted to washing out in-filled debris.

Carboniferous rocks were important to southern Arizona's mineralization and ore-development history. Many of the larger metallic mineral districts began with the mining of rich replacement deposits that formed in altered Carboniferous limestone. The close association of these limestones with mineralization explains their early study by geologists of the U.S. Geological Survey. Even today, the underground mining operation by the Magma Copper Co. at Superior is exploiting a copper-ore replacement body in the Mississippian Escabrosa Limestone.

In many southern Arizona localities, the Escabrosa and other limestones have been metamorphosed; one product is white marble, from which granules are used to make a reflective roof covering (no. 13).

Although there is no Arizona history of actual uranium extraction from Pennsylvanian rocks, anomalous uranium content is associated with possible Pennsylvanian carbonized plant zones along the Mogollon Rim. Certain petroleum tests north of the Mogollon Rim indicate that carbonaceous debris is widespread in the subsurface. A potential uranium source is the Precambrian granitic rock against which Pennsylvanian strata abut. Arkosic sandstone could exist near this unconformity and constitute a possible host for petroleum and/or uraniferous occurrences.

Carboniferous rocks constitute a vital part of Arizona's mineral resource base. Growth of the Southwestern United States assures a continuing and expanding demand for such fundamental products as cement and lime. Almost every building in Arizona is partly constructed from products derived from the processing of Carboniferous rocks.

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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—

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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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