in Jenney, J. P., and Reynolds, S. J., 1989, Geologic evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 313-347.

PENNSYLVANIAN AND PERMIAN GEOLOGY OF ARIZONA

by
Ronald C. Blakey
Department of Geology
Northern Arizona University, Flagstaff, Arizona 86011
and
Rex Knepp
Department of Geological Sciences
University of Arizona, Tucson, Arizona[1]

ABSTRACT

Pennsylvanian and Permian rocks are present in both outcrop and the subsurface across much of Arizona and surrounding areas. They record a varied depositional history that included sedimentation in continental, marine, and mixed sedimentary environments. Terminology and correlation are not agreed upon by various workers, reflecting the complex cyclic depositional nature of the rocks and the lack of reported fossils in several key horizons. In general, various regions of Arizona have independent rock-stratigraphic nomenclature, further adding to correlation and nomenclature problems. Correlation in this paper is based on available fossil data and physical correlation based on numerous surface and subsurface sections.

Pennsylvanian strata include dominantly carbonate rocks in the southeast, northeast, and northwest portions of Arizona and siliciclastic, primarily red rocks in the central and north-central portions of the state. All sections display complex cyclicity that reflects constantly changing sea level, tectonic activity, and possibly climate. Permian rocks, although also very cyclic, have less overall pattern than Pennsylvanian rocks. Local sections may vary greatly from nearby areas as facies changes are sharp and complex.

Based on regional correlation and the interpretation of depositional history, the Pennsylvanian and Permian depositional history is divided into eight phases. The contrasting depositional patterns seen in these phases reflect changing depositional controls throughout the period. During the Pennsylvanian, constantly changing sea level coupled with sporadic uplift and subsidence of local and regional tectonic elements produced the carbonate and siliciclastic cyclic sequences. Distribution of the three recognized phases of deposition primarily reflects subtle but important movements on basins and arches. Several of the five Permian phases were further complicated by the influx of large amounts of eolian sand from the north. The sand accumulated across and was deposited in vast eolian sand seas.

INTRODUCTION

Objectives and Methods

Pennsylvanian and Permian systems of Arizona represent a widespread complex of cyclic clastic and carbonate strata characterized by rapid lateral facies changes. Most previous studies of local to subregional extent have opted to use local terminology; however, a few have proposed regional correlation without sufficient data, and major miscorrelations are now in the literature. This paper comprehensively summarizes the Pennsylvanian and Permian geology of Arizona using the most modern data and methods. Only a limited review of older previous work will be given; much of the data and most of the interpretations reflect our recent studies in northern Arizona (Blakey, 1979a, 1979b, 1984; Blakey and Middleton, 1983) and southern Arizona (Knepp, 1983). Much of our local data is taken from numerous recent theses. Two major guidelines are followed throughout: (1) We will carefully separate data from interpretation, and (2) the sources of both data and interpretation, unless our own unpublished work, will be carefully cited. No attempt was made to standardize lithologic descriptions from unit to unit; generally, the terminology of the original author is used or slightly modified.

Pennsylvanian and Permian strata once covered most or all of Arizona, and areas of present outcrops are: Virgin Mountains, Arizona Strip, Marble and Grand Canyons, Monument Valley, Defiance Upwarp, Mogollon Rim and Slope, southeast and south-central Basin and Range province, and parts of the southwest Basin and Range (fig.

---

[1] Present address: 2770 S. Clarkson
Englewood, CO 80110

1). Only the extreme southwest portion of the state may have never been covered. The rocks are also present throughout the subsurface of northeastern Arizona. Our correlations indicate that in spite of complex cycles and facies changes, Pennsylvanian and Permian strata can be subdivided into prominent widely correlatable roughly time-equivalent sequences that may not correspond to existing stratigraphic units; we refer to these subdivisions as phases (fig. 2). Geologic history will be interpreted from analysis of each phase.

Geologic Setting

Analysis of Pennsylvanian facies and isopach map shows that Arizona was marginal to three distinct basins and that most of the state was dominated by intervening shelf (fig. 3). The shelf was subdivided by two prominent trends, the Sedona and Kaibab Arches (*not* uplifts), and bordered on the east by the Defiance Positive Area. Regional tectonic setting of Arizona is shown on figure 4.

Rocks of the Permian System form a sequence that in many areas is dominantly clastic at the base and carbonate at the top. The isopach map shows persistence of some Pennsylvanian patterns, including the Sedona Arch and the addition of the Holbrook Basin (fig. 5). Carbonate-clastic ratios reflect a persistent source of clastics to the north and northeast.

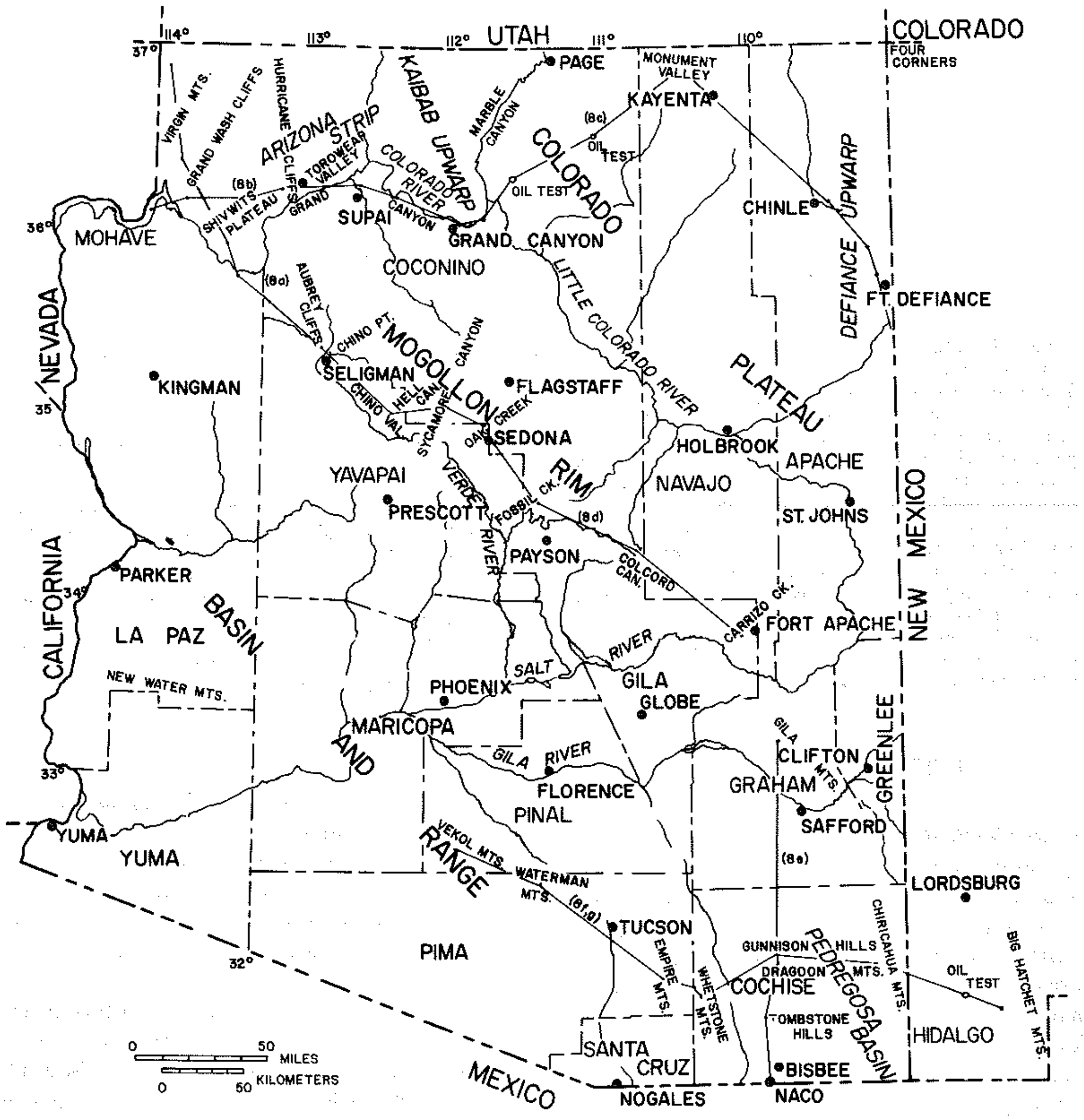
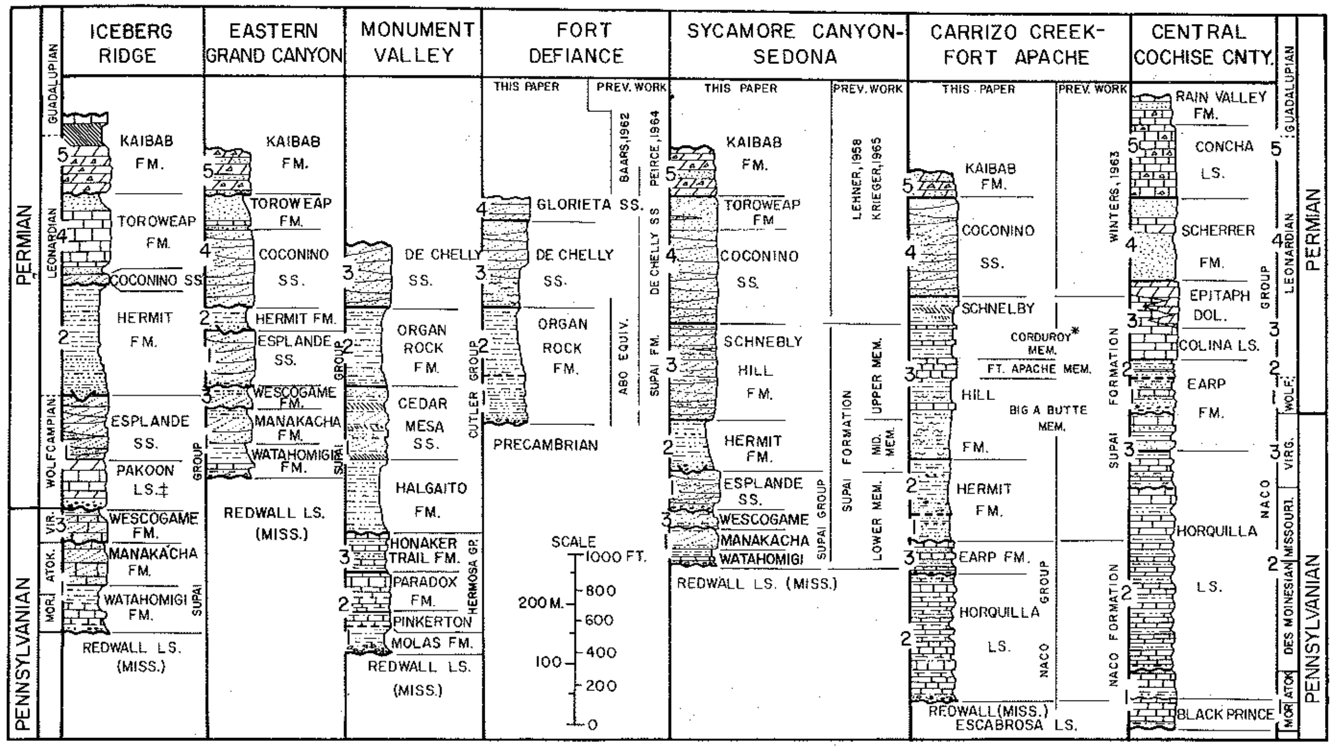


Figure 1. Map of Arizona showing locations mentioned in text and lines of cross-sections shown on figure 8.



‡ MC KEE(1982) DID NOT CONSIDER PAKOON TO BE A MEMBER OF THE SUPAI GROUP

*3 UPPER MEMBERS OF WINTERS(1963) REASSIGNED TO SCHNELBY HILL FM.

Figure 2. Selected columnar sections of Pennsylvanian and Permian rocks in Arizona showing present and selected previous nomenclature. Numbers correspond to phases of deposition and correlate columns to ages shown at left and right of figure. See figure 8 for explanation of lithologic symbols.

PENNSYLVANIAN STRATIGRAPHY

Introduction

Pennsylvanian rocks range from dominantly carbonate in the southeast and extreme northwest and northeast corners of the state to dominantly clastic in central and north-central Arizona (fig. 3). In most areas of mixed clastic-carbonate sequences, clastic content increases in younger parts of the section. Pennsylvanian strata range from unfossiliferous to extremely fossiliferous. Biostratigraphic correlation is well documented in northwestern (McKee, 1982) and southeastern (Ross, 1973) Arizona but is meager elsewhere.

Terminology and Correlation

Pennsylvanian terminology used in this report is predicated on the fact that Arizona bordered on three distinct basins (fig. 3). Sedimentation events and ages of strata are different in the three areas and independent nomenclature exists for each (figs. 2, 6, 7, 8).

The correlations shown in figures 6, 7, and 8 are based on fossil data, subsurface data, and careful detailed physical correlation, especially in the Mogollon Rim. Detailed accounts of methods of correlation were provided for Grand Canyon by McKee (1982), Mogollon Rim by Blakey (1979a, 1979b, 1980) and for southeast Arizona by Ross (1973) and Knepp (1983).

Supai Group

The Supai Group as defined by McKee (1975) comprises the following formations in ascending order: Watahomigi, Manakacha, and Wescogame Formations (Pennsylvanian) and Esplanade Sandstone (Permian). The group forms a westward-thickening wedge of dominantly clastic, coarsening-upward, red sedimentary rocks that becomes dominantly carbonate in extreme western Arizona and adjacent Nevada (fig. 8). Following the suggestion of McKee (1982), the term Callville Limestone is not used for the Grand Canyon region in this report although Callville continues to be used for southern Nevada and northwestern Arizona by some workers.

Watahomigi Formation. The Watahomigi Formation was named by McKee (1975) for exposures near Supai in central Grand Canyon. Detailed descriptions have been provided for exposures in Grand Canyon (McKee, 1982) and western Mogollon Rim (Blakey, 1979b). In both areas, the Watahomigi comprises cherty micritic limestone and terrigenous mudstone. The Watahomigi forms a wedge west of a line from Sedona to Page, Arizona (figs. 7, 8), and is herein recognized, along with the rest of the group, in the New Water Mountains near Quartzsite, Arizona (Miller

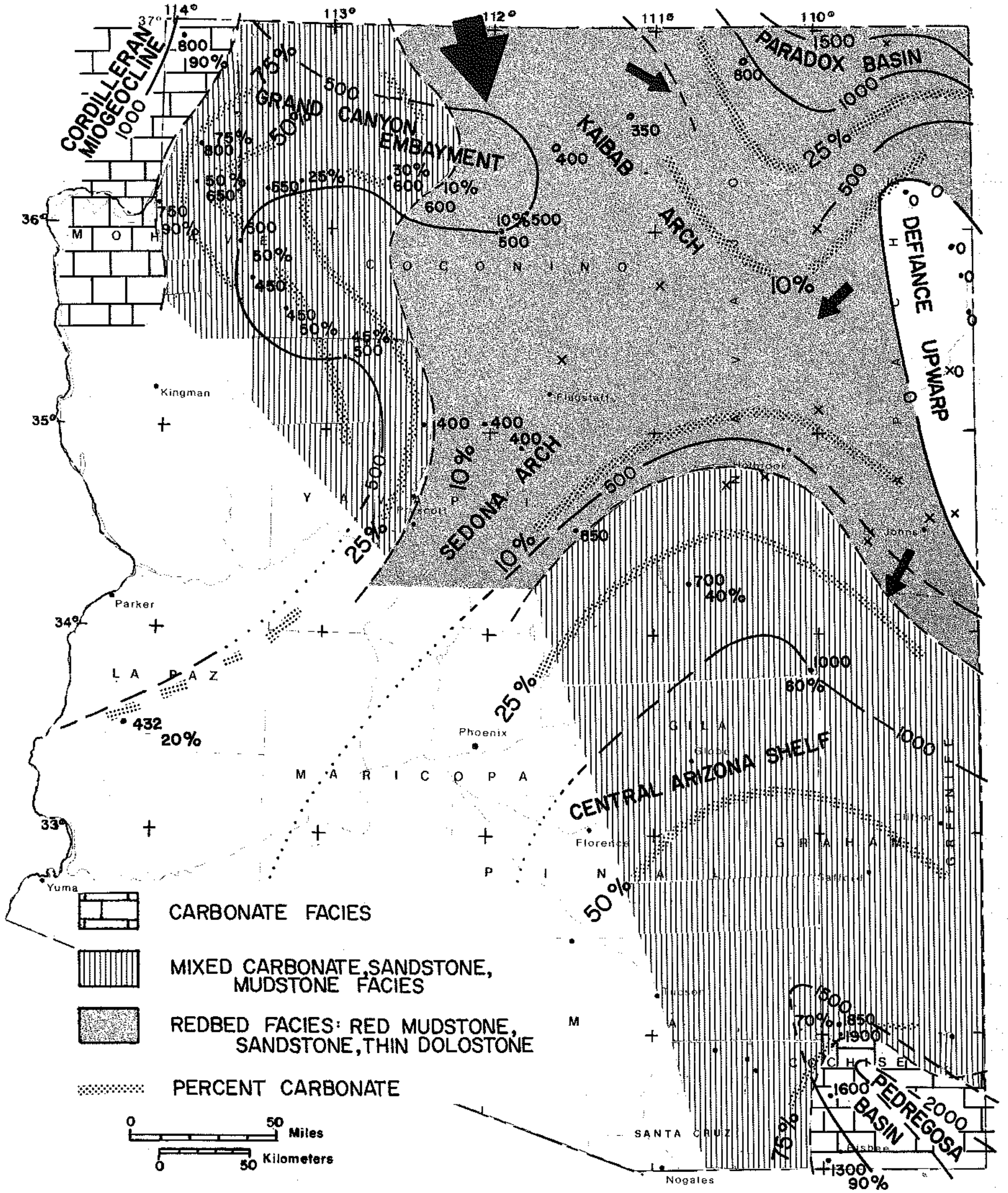


Figure 3. Isopach, facies, and carbonate-percentage map of Pennsylvanian System showing tectonic features. Isopachs in feet. Selected data points shown. Subsurface data points in northeastern Arizona after Irwin and others (1971).

and McKee, 1971), where a section nearly identical to that of the western Mogollon Rim occurs. Maximum reported thickness of about 100 m occurs in the Lake Mead-Grand Wash Cliffs area (McKee, 1982).

A diverse marine fauna yielded Morrowan and early Atokan ages for the Watahomigi in Grand Canyon (McKee, 1982, p. 107), and a similar fauna has been found in the western Mogollon Rim. This faunal age determination allows correlation of the Watahomigi with marine strata in adjacent areas (fig. 6). The Watahomigi unconformably overlies the Redwall Limestone or paleochannel-fill deposits described by Beus (this volume) and is overlain unconformably by the Manakacha Formation. Based on descriptions by McKee and Pierce (1982) and unpublished data gathered by Blakey for this report, eight lithofacies are recognized in the Watahomigi Formation (fig. 8; table 1).

Manakacha Formation. McKee (1975) named the Manakacha Formation near Supai in Grand Canyon. The unit has been described and defined in the Mogollon Rim (Blakey, 1979b) and Grand Canyon (McKee, 1982). The formation is dominated by large-scale, cross-stratified quartz sandstone and calcareous hybrid sandstone throughout most of its extent. Distribution of the Manakacha is the same as that of the underlying Watahomigi (figs. 7, 8); the two formations are separated by a change from slope-forming carbonate and fine-grained siliciclastic material below to dominantly cliff-forming sandstone above. Based on a well-documented marine fauna, the Manakacha is Atokan; McKee (1982) speculated that uppermost unfossiliferous beds might be partially Desmoinesian. However, at Iceberg Ridge on Lake Mead, the senior author carefully studied and sampled the beds in question. According to Raymond C. Douglass (personal commun., 1979) Atokan fusulinids were found within a few meters of Virgilian fusulinids in the overlying Wescogame Formation, so it is unlikely that Desmoinesian rocks are present in the Manakacha from Iceberg Ridge eastward to the Sedona Arch (fig. 6). Characteristic Desmoinesian fusulinids *Fusulina* and *Wedekindellina* were reported in the Virgin Mountains of extreme northwest Arizona (Welch, 1959); no Missourian fossils have been reported from northwest Arizona (McKee, 1982, p. 72). Four major and two minor facies constitute the Manakacha Formation in the Mogollon Rim, Grand Canyon, and Virgin Mountains (table 1). Description and interpretation of Manakacha cycles from the western Mogollon Rim are given in figure 9.

Wescogame Formation. The Wescogame Formation was named by McKee (1975) for exposures in the Grand Canyon near Supai. Due to complex intertonguing and rapid lateral facies changes, it is perhaps the most complicated formation in the Supai Group. Dominated by redbed clastics to the east, the formation changes rapidly to limestone in western Grand Canyon (McKee and Pierce, 1982, their fig. P10). In the western Mogollon Rim, the Wescogame is dominantly red sandstone and siltstone to the east, cyclic sandstone, siltstone, and thin limestone in the middle, and cross-stratified sandstone to the west (fig. 8). It forms a 30-60-m-thick blanket throughout its area of extent. It is the only Pennsylvanian sequence that crossed the Sedona and Kaibab Arches and was deposited in all three depocenters (fig. 7). Both the base and top are major regional unconformities (fig. 6). The Wescogame is firmly dated as Virgilian by a locally abundant marine fauna (McKee, 1982). McKee and Pierce (1982) recognized six facies in the Grand Canyon, three of which are present in the Mogollon Rim (table 1).

Black Prince Limestone

Gilluly and others (1954) formalized the Black Prince Limestone for exposures near the Black Prince mine in the

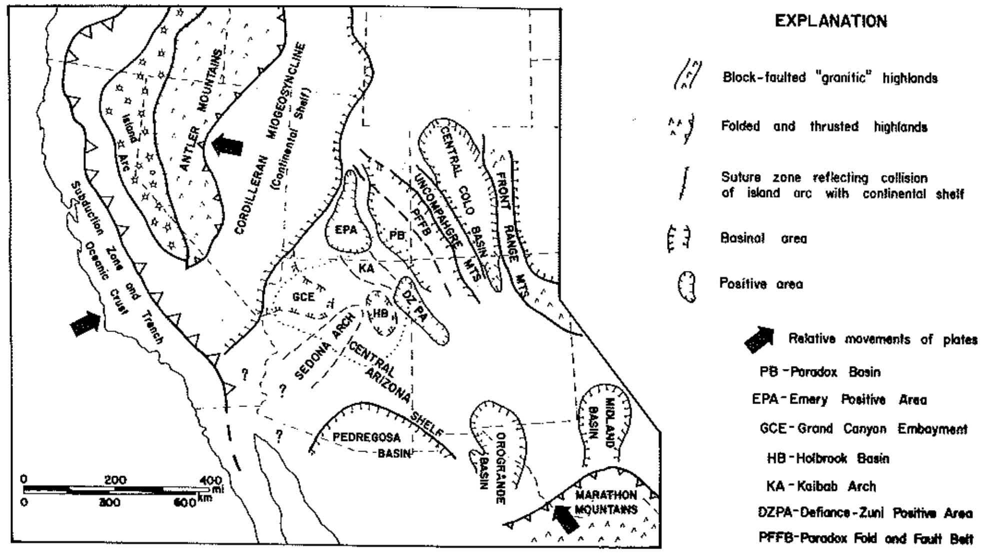


Figure 4. Late Paleozoic tectonic setting of Arizona showing major tectonic elements of southwestern United States (after Blakey, 1980).

Little Dragoon Mountains, designating a type section in the Gunnison Hills because of metamorphism at the Black Prince mine. At many locations the Black Prince comprises lower maroon mudstone and upper gray micritic limestone (table 1). Intercalations of skeletal limestone, cherty limestone, and mudstone are locally abundant. The Black Prince is of Morrowan to Atokan age. The original Mississippian age assignment (Gilluly and others, 1954) was based upon a reworked Escabrosa Limestone fauna found near the base of the formation (Nations, 1963).

The Black Prince was originally thought to occur only in a few ranges in northern Cochise County (Bryant, 1968; Nations, 1963). Ross (1973), however, identified Morrowan strata, which he assigned to the Black Prince, throughout southeastern Arizona and southwestern New Mexico. The isopach pattern of the Black Prince corresponds roughly to the outline of the Pedregosa Basin, with a general northwest-southeast trend and thickening toward the southeast. The Black Prince is bounded above and below by unconformities. The formation is generally 30 to 60 m thick, increasing to more than 100 m in southeastern Cochise County.

Naco Group

Gilluly and others (1954) raised the Naco Formation to group status and established six new formations: the Pennsylvanian Horquilla Limestone; the Pennsylvanian-Permian Earp Formation; and the Permian Colina Limestone, Epitaph Dolomite, Scherrer Formation, and Concha Limestone. Bryant and McClymonds (1961) defined a previously undescribed unit, the Rainvalley Formation, above the Concha.

Strata of the Naco Group crop out in mountain blocks throughout southeastern Arizona and southwestern New Mexico. Pennsylvanian carbonates and clastic rocks of the Horquilla Limestone and Earp Formation are present as far north as the Mogollon Rim (Ross, 1973) and as far west as the Vekol Mountains (Dockter and Keith, 1978), but Permian Naco units are unknown north of the Pima-Pinal County line, or west of Koht Kohl Hill near Silverbell (Bryant and McClymonds, 1961).

Horquilla Limestone. Gilluly and others (1954) named the Horquilla Limestone for a dominantly carbonate sequence exposed near Horquilla Peak in the Tombstone Hills. This ledge- and slope-forming unit is present in mountain ranges throughout southeastern Arizona. Ross (1973) correlated the Horquilla into the Mogollon Rim region where it had previously been called Naco Formation. Strata of the Horquilla consist of cyclically interbedded fossiliferous limestone and minor terrigenous mudstone and siltstone (fig. 10). Frequency and thickness of clastic beds increase up section as the Horquilla grades into the overlying Earp Formation. The Horquilla rests disconformably upon the Black Prince Limestone or Mississippian limestone of the Escabrosa (southern Arizona) or the Redwall (central Arizona). The Horquilla ranges in age from Atokan to Virgilian, although in its northernmost exposures, the base is of Desmoinesian age (fig. 6).

Earp Formation. The Earp Formation was established by Gilluly and others (1954) for a lithologically diverse sequence of interbedded limestone and fine clastics exposed at Earp Hill in the Tombstone Hills. Clastic units are typically calcareous, whereas carbonates are usually silty or clayey (table 1). Thickness of the Earp is difficult to determine because both contacts are gradational and somewhat arbitrary. The contact with the underlying Horquilla Limestone is assigned where fine clastic units become dominant over massive limestone. The upper contact is placed where the dark limestone of the Colina Limestone supersedes the interbedded clastic-carbonate lithologies of the Earp (Gilluly and others, 1954). Adding to the difficulty of determining the thickness is the problem of recognizing repetition or omission of section due to the faults that are common in this relatively incompetent unit (Bryant, 1968). In general, the Earp thins to the southwest and north and thickens to the southeast (Ross, 1973, figs. 21, 24). Fusulinid control places the age of the Earp as Virgilian to Leonardian? in southeastern Arizona (Ross, 1973); in southwestern New Mexico (Zeller, 1965; Thompson and Jacka, 1981) and southeasternmost Arizona (Drewes, 1982) the Horquilla-Earp contact falls above the Pennsylvanian-Permian boundary. Regional correlation is shown on figure 6.

Hermosa Group (Formation)

Wengard and Matheny (1958) raised the Hermosa Formation to group status and recognized in ascending order Pinkerton Trail, Paradox, and Honaker Trail Formations of the Hermosa Group. These three formations can be recognized in extreme northeastern Arizona; however, in most of northeastern Arizona, dominantly unfossiliferous redbeds and dolomitic sandstone form a poorly understood Pennsylvanian sequence generally referred to as Hermosa Formation (Baars and others, 1967; Pope, 1976). For convenience, dominantly clastic, basal Pennsylvanian strata that might be more accurately assigned to the Molas Formation in a detailed study, are herein included with the Hermosa. The Hermosa Group thins abruptly from 600 m thick in the Paradox Basin at Four Corners to 100 m thick across most of northeastern Arizona (figs. 3, 8).

PENNSYLVANIAN-PERMIAN BOUNDARY

The position and nature of the Pennsylvanian-Permian boundary in Arizona remains unclear. In most locations where both systems are present, 30-100 m of unfossiliferous rocks separate known Pennsylvanian and Permian rocks. The amount of time missing at most locations is probably indeterminable. The following discussion of several areas illustrates the problem (fig. 11):

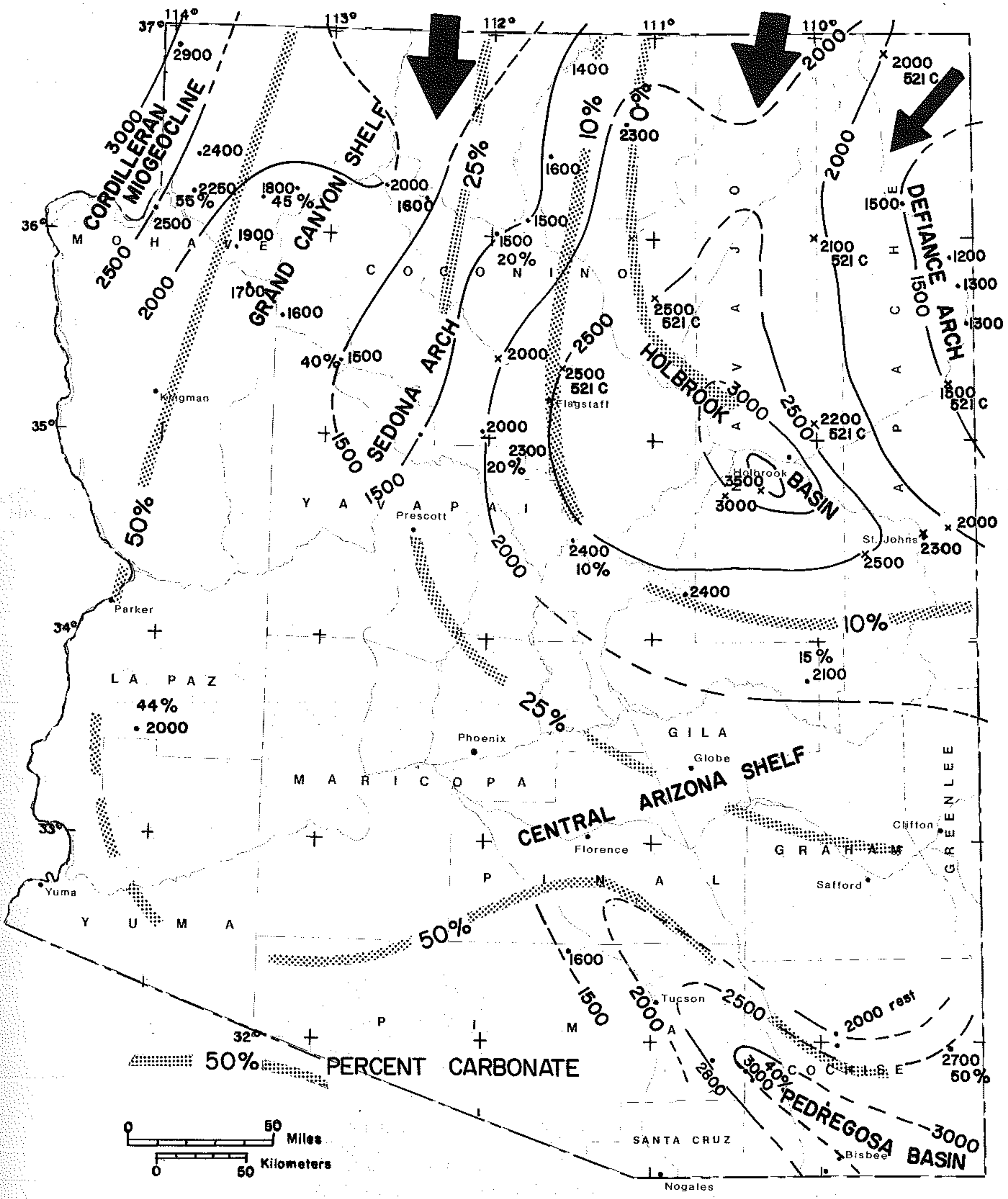


Figure 5. Isopach and carbonate-percentage map of Permian System showing tectonic features. Isopachs in feet. Selected data points shown. Subsurface data points in northeastern Arizona after Irwin and others (1971).

1. Throughout Grand Canyon McKee (1982) reported the presence of a widespread erosion surface and associated conglomerate between the Wescogame Formation and Esplanade Sandstone. Careful physical correlation of this surface into unfossiliferous rocks in the western Mogollon Rim (Blakey, 1979a, 1979b, 1980) established the systemic boundary as far east as Oak Creek Canyon.

2. East of Oak Creek the Esplanade Sandstone is absent. At Fossil Creek, sandstone and mudstone of the Pennsylvanian Earp Formation are succeeded by intercalated sedimentary-pebble conglomerate, gray mudstone, and local coal. This sequence is overlain by redbeds of the Permian Hermit Formation. The boundary most likely occurs at the base or within the gray sequence. From near Payson eastward, a thin ledge-forming limestone that yields a Virgilian fauna (Brew, 1965) is succeeded by redbeds and local gray mudstone and conglomerate. This interval yields a probably Wolfcampian plant flora in a few places (Canright, 1978). Here the boundary lies above the limestone and below the Permian flora. Unfortunately none of the above lithologies or sequences persists throughout the Mogollon Rim, so lateral establishment of the boundary remains controversial at present.

3. Across most of the Defiance Uplift, Permian strata rest directly on Precambrian rocks. Where Pennsylvanian strata are present in the subsurface of northeastern Arizona, the boundary cannot be picked with any degree of certainty because Pennsylvanian redbeds are overlain by Permian redbeds.

4. In southeastern Arizona precise location of the systemic boundary has always been problematic because of the possible continuity of deposition across the boundary and, in most areas, paucity of biostratigraphic control. The boundary has historically been placed within the lower Earp Formation, based upon fusulinid data (Gilluly and others, 1954; Rea and Bryant, 1968). In ranges marginal to the Pedregosa Basin facies, it falls within the upper Horquilla Limestone (Drewes, 1981, Chiricahua Mountains; Thompson and Jacka, 1981, Big Hatchet Mountains).

PERMIAN STRATIGRAPHY

Introduction

Permian strata are widespread and of variable lithology; many sections are dominated by clastic rocks that grade

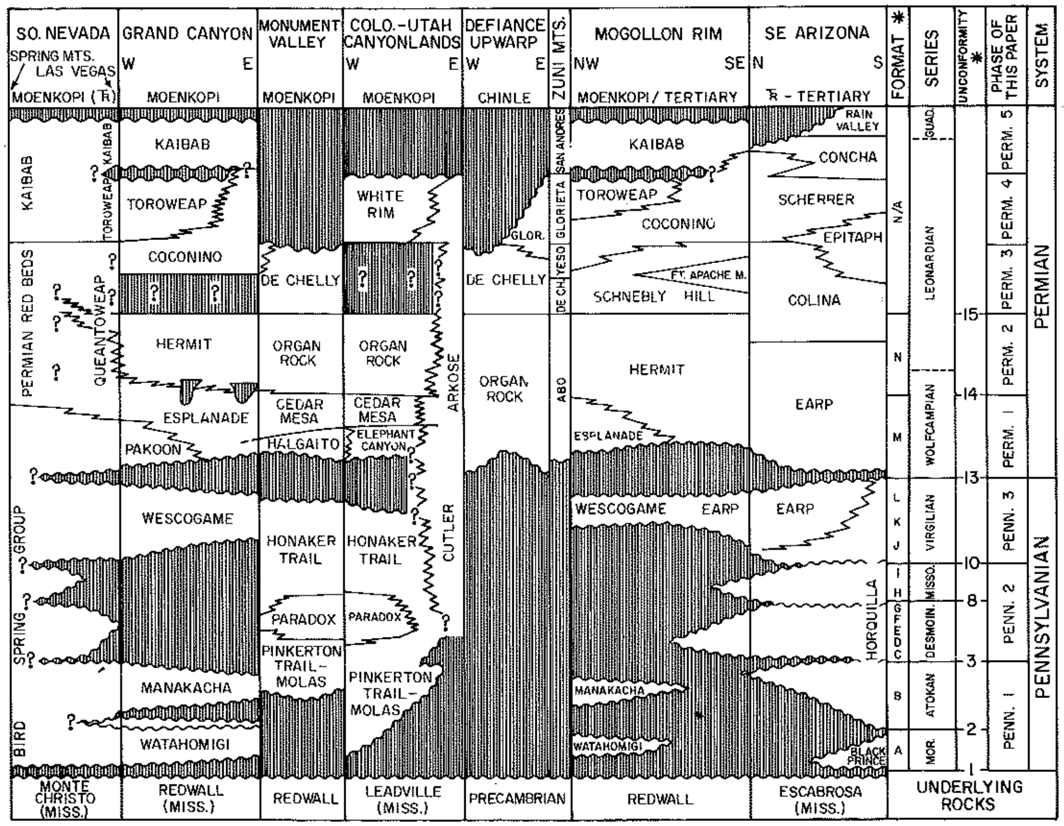


Figure 6. Time-rock stratigraphic chart of Pennsylvanian and Permian of Arizona and adjacent areas. Also shown are relations of series to formats and unconformities of Ross (1973) and phases of deposition (this paper).

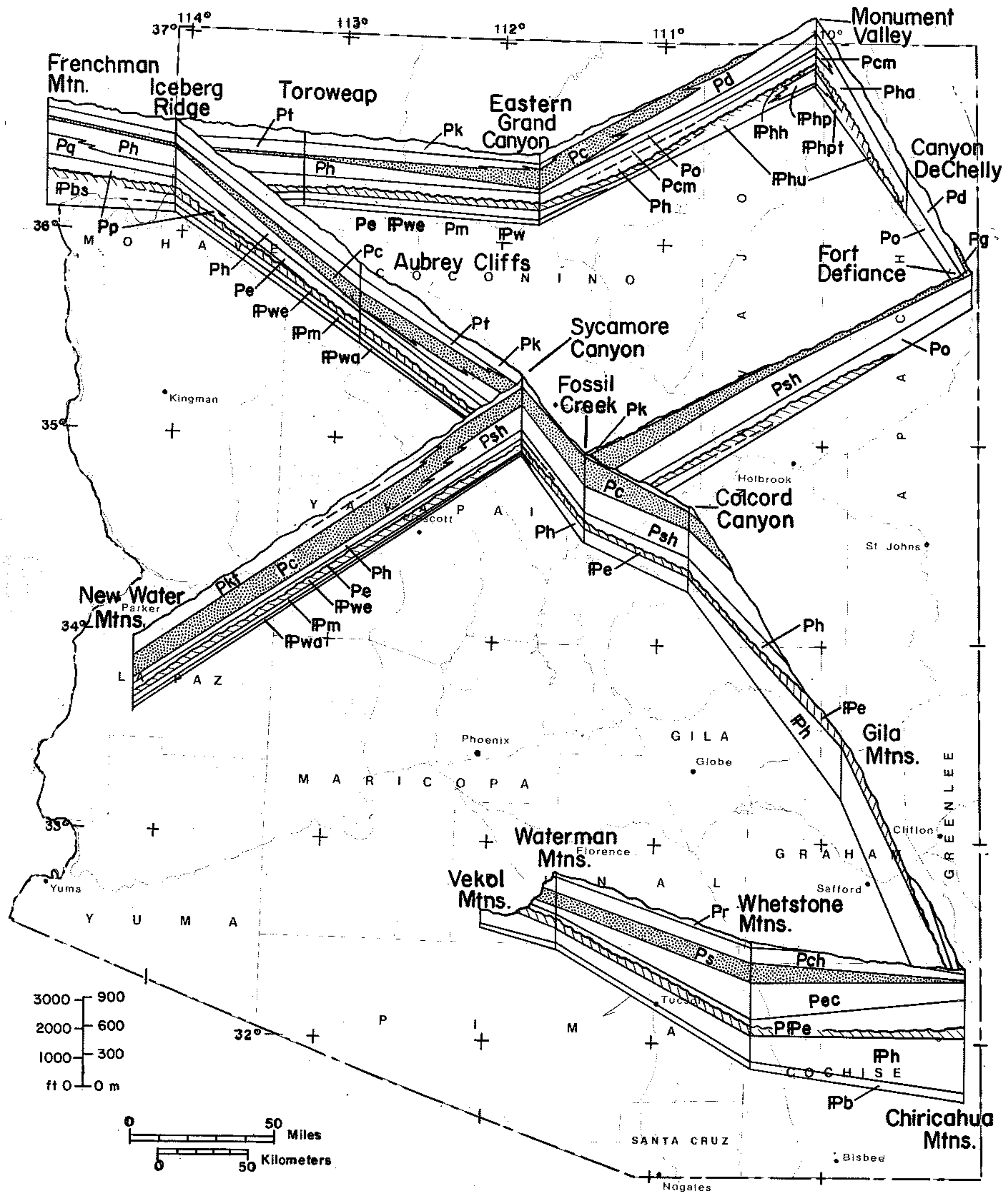


Figure 7. Fence diagram of Pennsylvanian and Permian rocks of Arizona based on present geographic location of sections. List of symbols: IPb-Black Prince Ls, IPh-Horquilla Ls, IPe, PIPe-Earp Fm, IPwa-Watahomigi Fm, IPm-Manakacha Fm, IPwe-Wescogame Fm, IPhu-Hermosa Fm, undivided, IPhpt-Pinkerton Trail Fm, IPhp-Paradox Fm, IPhh-Honaker Trail Fm, Pp-Pakoon Ls, Pq-Queantoweap Ss, Pe-Esplanade Ss, Ph-Hermit Fm, Pec-Epitaph Fm and Colina Ls, IPbs-Bird Spring Group, undivided, Pha-Halqaito Fm, Pcm-Cedar Mesa Ss, Po-Organ Rock Fm, Pd-De Chelly Ss, Pg-Glorieta Ss, Psh-Schnebly Hill Fm, Pc-Coconino Ss, Pt-Toroweap Fm, Pk-Kaibab Fm.

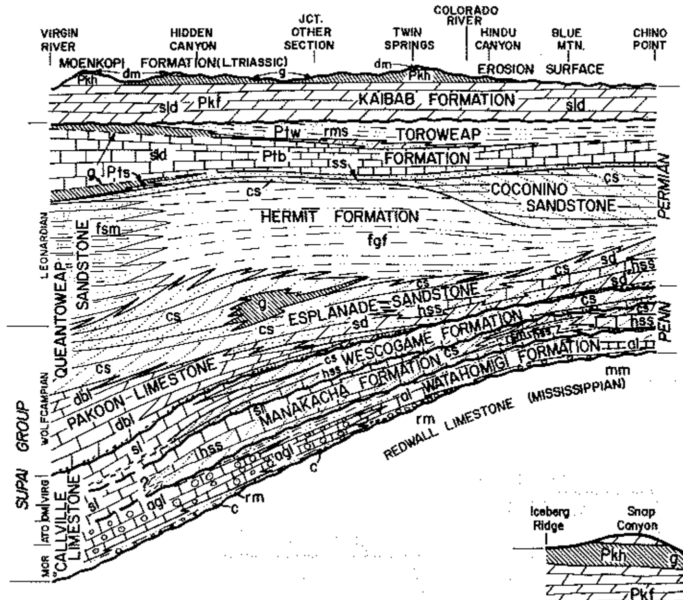


Figure 8a.

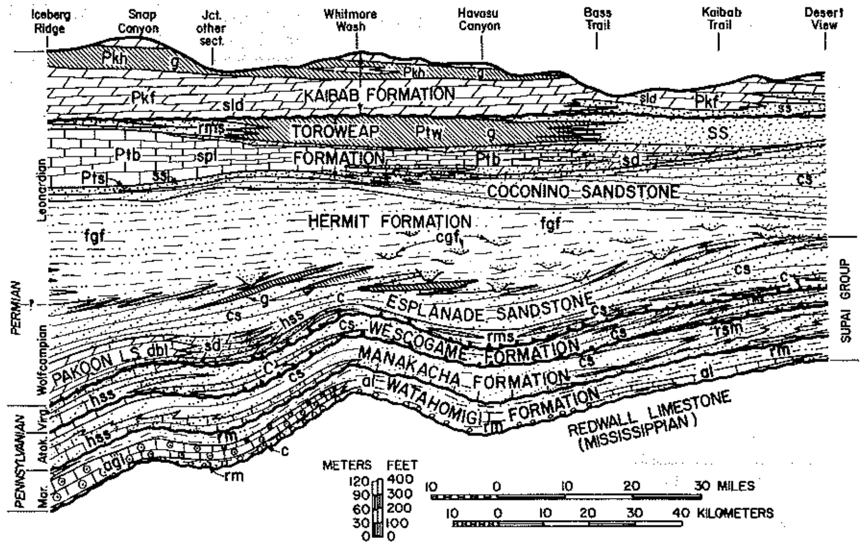


Figure 8b.

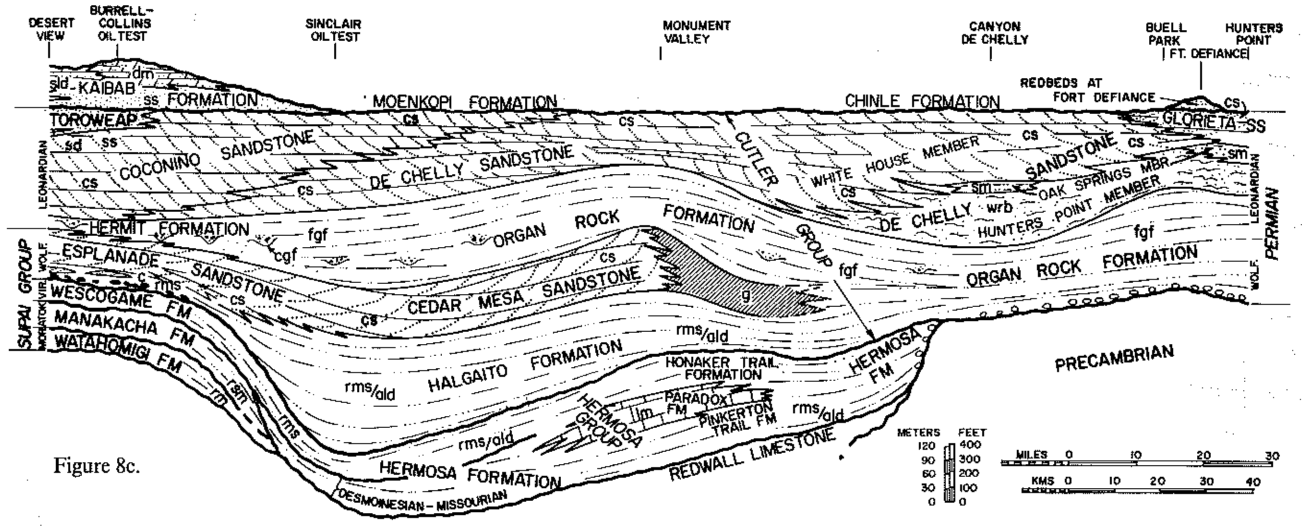


Figure 8c.

Figure 8. Restored lithologic cross-sections of Pennsylvanian and Permian rocks of Arizona. Lower-case letters refer to facies of table 1. Members of Toroweap and Kaibab Formations—Pts: Seligman Member; Ptb: Brady Canyon Member; Ptw: Woods Ranch Member; Pkf: Fossil Mountain Member; Pkh: Harrisburg Member. Sources of data not discussed in text include: Bissell (1969; Grand Canyon region), Brown (1969; Kaibab Formation), Fisher (1961; Grand Canyon region), Sorauf (1962; Grand Canyon region), Steed (1980; Virgin River Gorge). Note that position of "Callville Limestone" of previous workers is shown in Virgin Mountains and that Desmoinesian strata in northwestern Arizona are restricted to the Virgin Mountains. Slightly different lengths of sections F and G are due to different routes of Pennsylvanian and Permian sections.

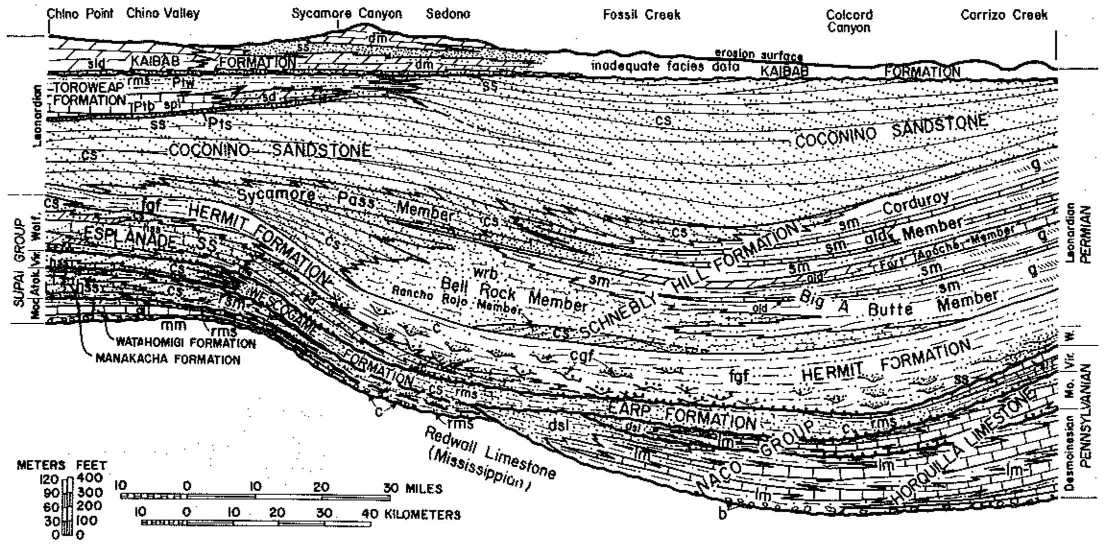


Figure 8d.

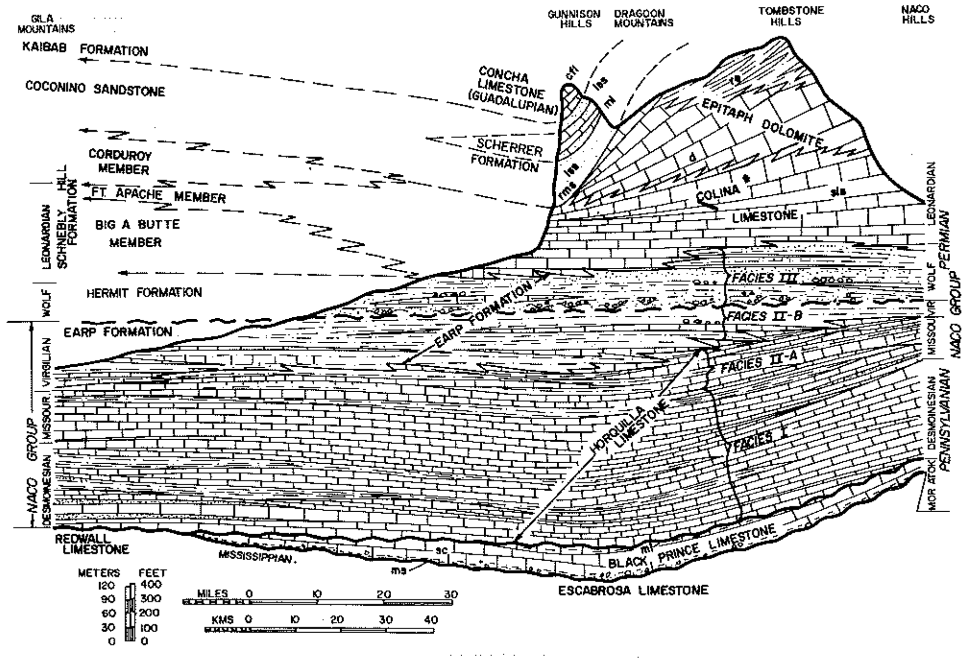


Figure 8e.

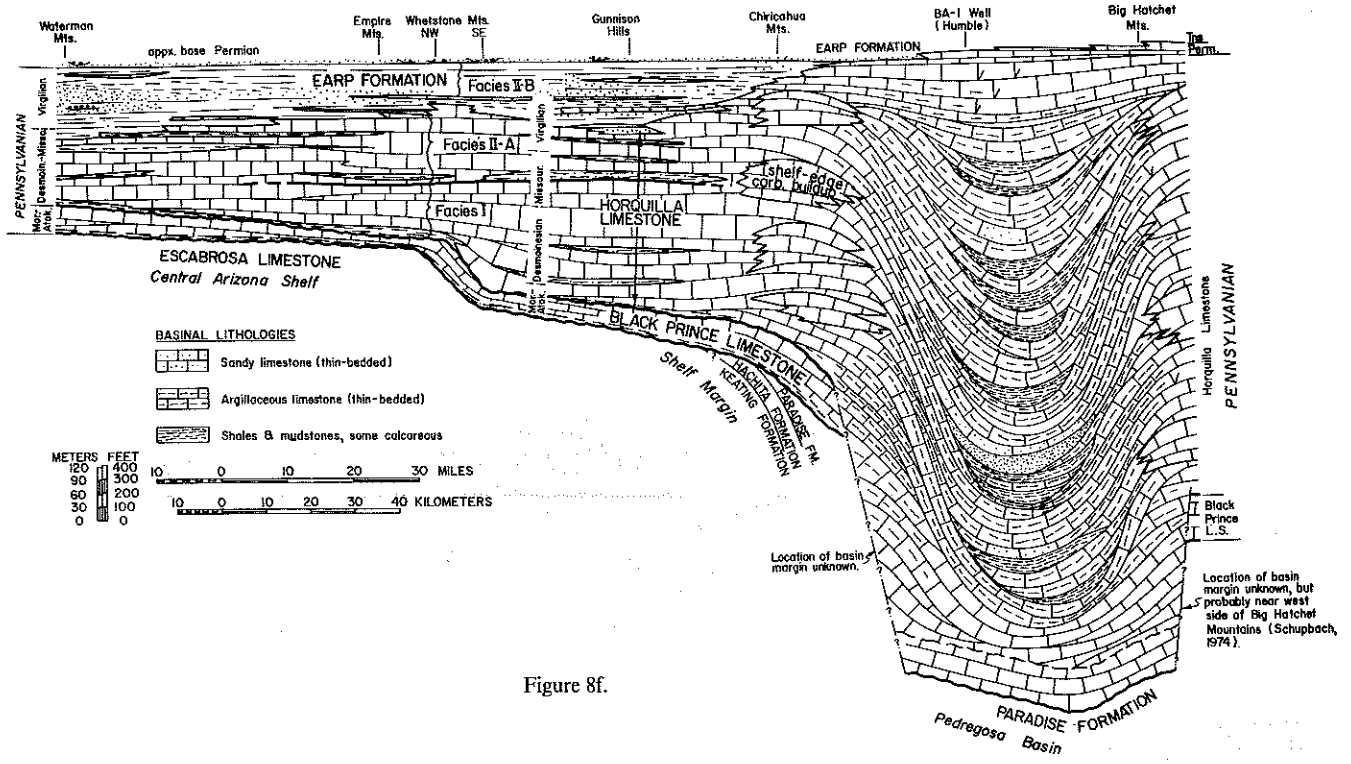


Figure 8f.

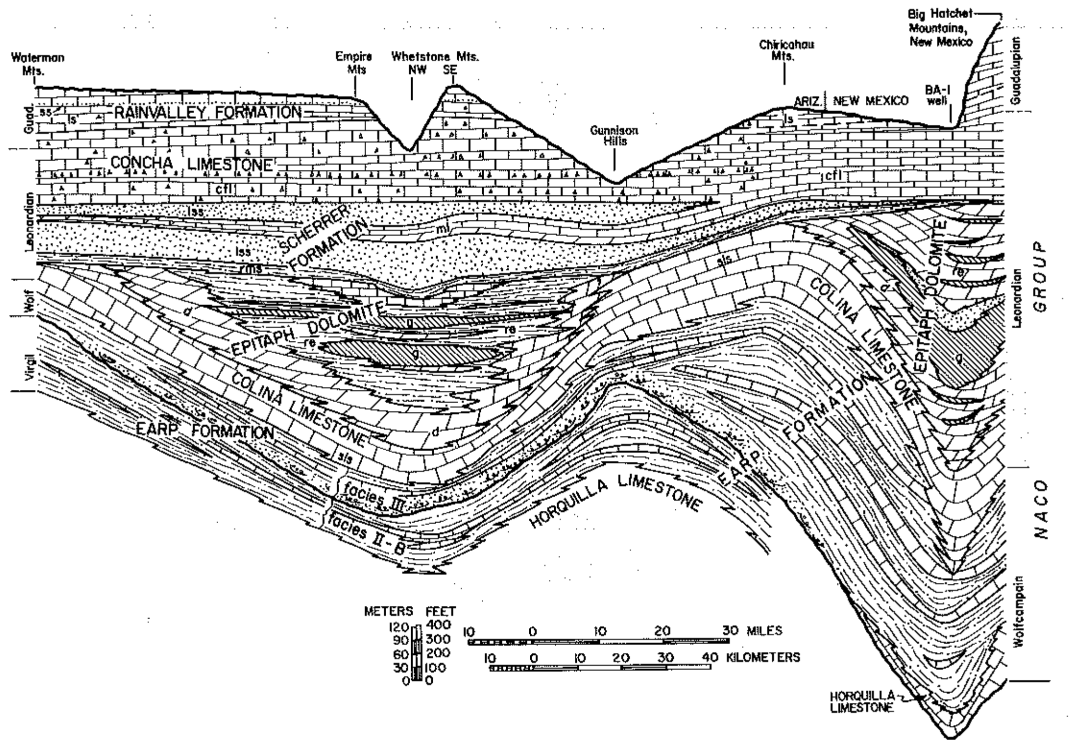


Figure 8g.

upward into carbonates. Carbonate percentage is increased in both the northwest and southeast portions of the state. Fossil data and biostratigraphic correlation are generally poorer than in Pennsylvanian rocks (fig. 6). However, biostratigraphic correlation of several key carbonate units provides a framework for regional correlation (figs. 2, 6, 7, 8).

Quartz sand was fed into the state from the northwest and three geographically and stratigraphically distinct quartz arenite sequences were formed: (1) Cedar Mesa-Esplanade-Queantoweap assemblage, which thickens westward and intertongues with carbonates of the Cordilleran Miogeocline; (2) De Chelly-Schnebly Hill assemblage, which thickens into and rims the Holbrook Basin; and (3) the southward-thickening Coconino Sandstone, which was trapped on the Central Arizona Shelf north of the Pedregosa Basin.

Terminology and Correlation

Permian terminology used in this report generally conforms to former usage with separate nomenclature used in the Monument Upwarp, Grand Canyon, and southeastern Arizona regions (fig. 6). Greatest controversy occurs throughout the Mogollon Rim (Peirce and others, 1977; Baars, 1979; Blakey, 1979b, 1980; Elston and DiPaolo, 1979). The correlation and terminology used herein evolved from the work of Lane (1977) and Blakey (1979a, 1979b, 1980). Correlation along the Mogollon Rim is based on (1) paleontologic data that shows that the Schnebly Hill Formation is considerably younger than the type Supai Group; (2) careful tracing of the Esplanade Sandstone and Hermit Formation from the Aubrey Cliffs to Sedona; and (3) extremely detailed local and regional stratigraphic, sedimentologic, and petrographic studies (Blakey, 1979a, 1979b, 1984; Blakey and Middleton, 1983; Lane, 1979; Gallaher, 1984; Duffield, 1985; McAllen, 1984).

Supai Group

Though once considered to be wholly or chiefly Permian, the Supai is now known to contain subequal portions of Pennsylvanian and Permian rocks (McKee, 1982). The Permian portion consists of the Esplanade Sandstone and coeval Pakoon Limestone and Queantoweap Sandstone (Bissell, 1969).

Esplanade Sandstone. Named for exposures in cliffs and ledges near Supai, the Esplanade Sandstone is the youngest formation in the Supai Group (McKee, 1975). The formation has been described by McKee (1982) in Grand Canyon and Lane (1977, 1979), Blakey (1979a, 1979b, 1980), and McAllen (1984) in the Mogollon Rim. The basal Esplanade consists of red, slope-forming, dolomitic sandstone, siltstone, and conglomerate. It is succeeded by thick, cross-stratified sandstone and hybrid sandstone; locally present are an upper ledge- and slope-forming sandstone and mudstone (fig. 8). In western Grand Canyon, the lower portion grades westward into the Pakoon Limestone (McKee, 1982). The Esplanade and its northern equivalent, the Cedar Mesa Sandstone, thicken westward from a zone of facies changes along the Sedona Arch to a zone of facies changes in the eastern Cordilleran Miogeocline. In most areas, this vast sandstone sheet ranges from 100-300 m in thickness (fig. 8).

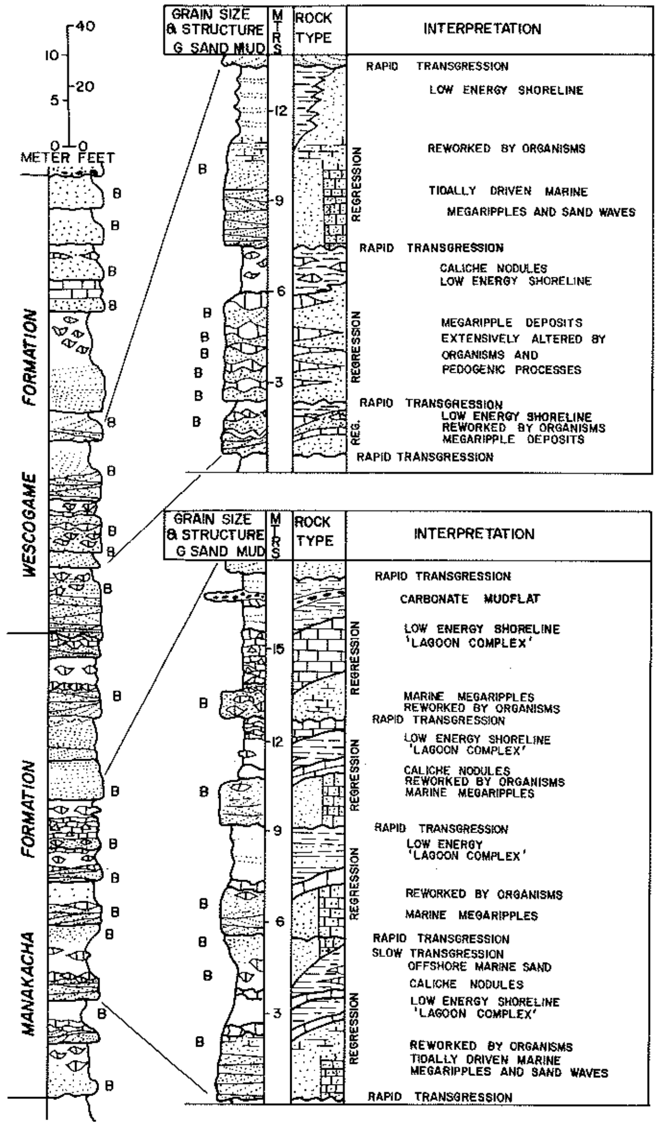


Figure 9. Complete columnar sections and detailed partial lithologic logs of Manakacha and Wescogame Formations at Hell Canyon, western Mogollon Rim, showing cyclicity and interpretation of cycles. Manakacha-Wescogame boundary placed above possible paleoweathered zone correlated throughout region by Gallaher (1984). Work in progress by Blakey suggests that some cross-stratified sandstone units are eolian in origin. When finalized, this work will alter interpretations shown herein. See figure 10 for explanation of symbols.

Though good time-sensitive fossils have not yet been reported in the Esplanade, intertonguing with the Wolfcampian Pakoon Limestone establishes a Wolfcampian age for all or most of the formation (McKee, 1982, p. 111). The Esplanade unconformably overlies the Wescogame Formation except in western Grand Canyon where it gradationally overlies the Pakoon Limestone. The contact

TABLE 1. Facies description and interpretation.

Facies	Description	Interpretation
Watahomigi Formation (Morrowan-Atokan)		
Jasper-pebble conglomerate (c)	Conglomerate, mostly grain-supported chert. Scattered quartz grains; rare limestone and siltstone pebbles; locally fossiliferous. Bedding ranges from structureless to crudely horizontally stratified. Lies unconformably on Redwall Limestone. Discontinuous throughout Grand Canyon (McKee, 1982) and western Mogollon Rim (Blakey, 1979b).	Basal transgressive marine conglomerate (rare marine fauna) throughout Grand Canyon (McKee, 1982, p. 189). Of undocumented but probably similar origin in Mogollon Rim.
Mottled Maroon mudstone (mm)	Mudstone, siliceous, mottled maroon and white, probably kaolinitic.	Origin uncertain; possibly low-energy shoreline deposit subjected to intensive postdepositional weathering.
Aphanitic limestone (al)	Peloidal wackestone, cherty, clotted, unfossiliferous to very fossiliferous. Chert clearly secondary. Bedding indistinct to slightly wavy.	Somewhat restricted carbonate marine shelf (Blakey, 1980; McKee, 1982). Wave and tidal energy dissipated far offshore to west (Iceberg Ridge).
Accretal and mixed-grain limestone (agl)	Grainstone and packstone, coated skeletal grains, abraded, somewhat sorted; indistinct laminations with minor (one occurrence) cross-stratification (McKee and Pierce, 1982, p. 346-7). We saw extensive planar-wedge cross-stratification at Iceberg Ridge.	Shallow marine, possibly high-energy shelf though absence of cross-stratification puzzling (McKee and Pierce, 1982, p. 347). Section at Iceberg Ridge appears to resemble classic oolite shoal. This suggests shelf break in this region.
Crystalline dolostone (cd)	Dolomite, coarsely crystalline; original fabric destroyed.	Uncertain, diagenetic alteration probably of shallow-marine limestone.
Red mudstone (rm)	Terrigenous mudstone, calcareous, structureless to ripple-laminated, poorly exposed.	Origin uncertain; stratigraphic position suggests low-energy shoreline and coastal-plain environments.
Orange calcareous sandstone (ss)	Quartz sandstone, structureless to bioturbated to planar cross-stratified, very fine grained.	Origin uncertain; probably medium-energy coastal sequence but could be fluvial.
Manakacha Formation (Atokan)		
Red sandstone and mudstone and associated coarsely crystalline dolostone (rsm)	Sandstone, dark-reddish-brown, structureless to bioturbated to cross-stratified; forms ledges. Mudstone, structureless to ripple cross laminated; dolostone structureless, sandy, bioturbated;	Chiefly formed on more restricted areas of marine clastic shelf (suggested by stratigraphic position). Cyclic sequence in Rim formed by repeated transgressive-regressive cycles; see fig. 9.
Manakacha Formation (Atokan)		
Cross-stratified quartz sandstone (cs)	Sandstone, very fine grained, quartz and minor (up to 30%) peloidal grains; cross-stratified planar-wedge, planar-tabular, and compound (intraset) sets and cosets several meters thick. Stratification dips southerly. Abundant jasper or carbonate bands parallel to lamination.	High-energy siliciclastic marine shelf (McKee and Pierce, 1982). Sand waves and megaripples migrated southerly across shelf. Many larger bedforms had superimposed smaller bedforms. Some sets probably of eolian origin.
Calcareous sandstone to peloidal limestone (hss)	Sandstone with greater than 30% carbonate (chiefly peloidal) grains. Stratification similar to that of cross-stratified quartz sandstone.	High-energy siliciclastic-carbonate shelf; mechanical origin of hybrid sandstone not well understood.
Skeletal limestone (sl)	Skeletal grainstone and packstone with normal marine fauna.	Open-marine medium-to high-energy carbonate shelf. Eastward extension to central Grand Canyon may represent lull in quartz-sand influx.
Conglomerate (c)	Chert-, limestone-, and quartz-pebble conglomerate.	Origin and significance of minor occurrences unclear. Both siliceous and sedimentary pebbles derived from underlying units.
Wescogame Formation (Virgilian)		
Red mudstone and sandstone (rms)	Description as per same facies in Manakacha.	Probably of variable origin including shoreline, coastal-plain, and possible fluvial.
Cross-stratified quartz sandstone (cs)	Similar to that of Manakacha though McKee (1982) reported trough cross-stratification, a rare feature in the Manakacha.	McKee (1982) vacillated on origin of Wescogame sandstone though favored a fluvial origin in much of Grand Canyon. Cyclic Rim sections (with local abundant herringbone cross strata) probably marine shelf and shoreline (Blakey, 1980). Some units of eolian origin. Detailed regional study needed.
Calcareous hybrid sandstone to peloidal limestone (hss)	Similar to that of Manakacha.	High-energy shelf (see Manakacha).
Skeletal limestone (sl)	Similar to that of Manakacha.	Open-marine (see Manakacha).
Thin-bedded dolostone (cd)	Crystalline dolomite.	Unknown; probably diagenetic.
Conglomerate (c)	Micritic limestone- and chert-pebble conglomerate; matrix of gray carbonate or brown calcareous siltstone.	Represents reworked underlying Supai during long period of erosion; origin unspecified (McKee, 1982).

TABLE 1. Facies description and interpretation. (Continued)

Facies	Description	Interpretation
Horquilla Limestone of Mogollon Rim (Desmoinesian-Missourian)		
Breccia and conglomerate (b)	Mudstone, sandstone, limestone, chert breccia, and chert-pebble conglomerate, reddish, mottled. Deposited on surface and fills in swales and caverns of underlying Redwall Limestone.	Karst, pedogenic, and basal marine deposits (Brew, 1965).
Limestone and mudstone (lm)	Limestone and mudstone, intercalated; cyclic, fossiliferous. Limestone includes skeletal calcarenite and calcilutite, local calcirudite, and algal-laminated micritic limestone. Mudstone, bluish-green to purple, calcareous, locally fossiliferous with whole, unabraded brachiopod and bryozoan remains.	Cyclic transgressive-regressive marine shelf deposits (Brew, 1965; Ross, 1973). Carbonate shoreline, shoal, open-shelf and mudstone shelf deposits represented.
Dolomitic sandstone, limestone, and mudstone (dsl)	Varied catch-all facies of cyclic pinkish-gray clastic and carbonate rocks that have not been well studied. Cycles 2-6 meters thick, clastic content increases up cycle. Minor cross-stratified sandstone, locally abundant in Fossil Creek.	Stratigraphic position (fig. 8) suggests shoreline and coastal-plain deposition. Sand derived from northwest.
Earp Formation of Mogollon Rim (Virgilian)		
Skeletal limestone (sl)	Limestone, gray with distinctive salmon-colored fossil grains; fossils locally silicified. Texturally includes packstone and grainstone. Typical Pennsylvanian shallow-marine fauna.	Moderate to high-energy carbonate shelf. Typically enclosed in sandstone or mudstone, so probably represents periods of slight clastic influx.
Sandstone (ss)	Quartz and calcareous hybrid sand stone. Horizontally laminated to cross-stratified, generally reddish. Associated with skeletal calcarenite; poorly studied.	Uncertain; hybrids contain marine fauna. Probably shelf and shoreline deposition during clastic influx. Possibly tidal and estuarine environments (Ross, 1973).
Red mudstone and sandstone (rms)	Similar to that of Wescogame Formation. Dominates Earp in Fossil Creek area. Interbedded with above facies to east.	Variable origin; probably includes shoreline, coastal-plain, and fluvial deposits.
Conglomerate (c)	Sedimentary-pebble conglomerate most common (similar to that of Supai Group).	Uncertain; some probably fluvial; possibly marine storm deposits.
Esplanade-Queantoweap-Cedar Mesa-Pakoon-Halgaito (Wolfcampian)		
Red mudstone and sandstone (rms)	Similar to that previously described.	Intertongues basinward with marine carbonate so probably somewhat restricted clastic shoreline to coastal-plain deposit.
Esplanade-Queantoweap-Cedar Mesa-Pakoon-Halgaito (Wolfcampian)		
Cross-stratified quartz sandstone (cs)	Quartz arenite, very fine to medium-grained. Two types: (1) similar to that of Manakacha; (2) large-scale, high-angle planar-tabular to planar-wedge cross-stratification with prominant sandflow toes and associated climbing translatent strata. Two types may be separate or closely associated. Type two most abundant near top of Esplanade and Queantoweap (Johansen, 1981; McAllen, 1984).	Type one was formed on high-energy marine shelf and shore-shoreline (tidal sandwave and beach environment.) McKee (1982) generally assigned a fluvial-estuarine environment. Type two is eolian and is part of first major Paleozoic eolian deposition in northern Arizona. Loope (1984) favored total eolian origin for Cedar Mesa Sandstone; other workers favored mixed marine-eolian interpretation (Baars, 1962; Mack, 1979; Blakey, 1980).
Calcareous sandstone and peloidal limestone (hps)	Similar to that of Manakacha.	High-energy marine shelf (see Manakacha).
Sandy dolostone (sd)	Dolostone and sandy dolostone, structureless to bioturbated to faintly cross-stratified.	Cross-stratified units represent dolomitized hybrid sandstone (McAllen, 1984). Origin of other types uncertain; probably coastal-plain.
Dolostone and bioclastic limestone (dbl)	Skeletal packstone and wackestone, abundant pelmatozoans; accretal grains absent; dominant facies in Pakoon Limestone (McKee and Pierce, 1982).	High-energy marine (McKee and Pierce, 1982, p. 357).
Bedded gypsum (g)	Bedded gypsum, light-gray; widely distributed in Esplanade (McKee and Pierce, 1982) and Queantoweap (Johansen, 1981) in northwest Arizona and Cedar Mesa (Baars, 1962) of Monument Valley.	Restricted-marine, sabkha, or lagoon.
Conglomerate (c)	Sedimentary-pebble (micritic limestone, limey siltstone and sandstone) conglomerate with scarcity of siliceous pebbles. Gravel fills channels up to 15 m deep. Base of Esplanade-Pakoon throughout Grand Canyon (McKee, 1982) and parts of Mogollon Rim (Blakey, 1979a, 1979b, 1980).	Fluvial channel-fill and interfluve deposits (McKee, 1982). Pebbles exclusively locally derived. Unconformity marks Pennsylvanian-Permian boundary (McKee, 1975, 1982; Blakey, 1979a, 1979b, 1980).

TABLE 1. Facies description and interpretation. (Continued)

Facies	Description	Interpretation
Hermit-Organ Rock-upper Queantoweap (Wolfcampian and Leonardian)		
Coarse-grained facies (cgf)	Sandstone, dark-reddish-brown, very fine grained, calcarous, plane-bedded, ripple cross-laminated, trough cross-stratified, local epsilon cross-stratification; sedimentary-pebble conglomerate, generally identical to that of Esplanade. Facies occurs in lenses up to several tens of meters thick and probably up to 1 km or more wide (Duffield, 1984) or as thin broad sheets less than several meters thick. Facies widely distributed throughout Hermit and Organ Rock but most abundant in Mogollon Rim from Sycamore Canyon to Fossil Creek (Blakey 1979b, 1980). Plant fossils locally abundant.	Fluvial. In Sedona area, two scales of channels present; large: 20-30 m thick and 1 or more km wide; some exhibit classic point-bar sequence; small: few meters thick and tens of meters wide with irregular cut-and-fill troughs; ripple lamination common. Large channels are major meandering streams, smaller are tributaries or ephemeral streams (Duffield, 1984). Sheetlike deposits may have been formed by broad, ephemeral streams. Not all coarse deposits are necessarily fluvial, and suggestion that stratigraphic position infers nearby marine conditions (Blakely, 1980) needs testing.
Fine-grained facies (fgf)	Mudstone, siltstone, thin ripple cross-laminated sandstone, reddish-brown, generally poorly exposed. Local abundant plant fragments. Widely distributed, all areas.	Flood-basin and possibly locally coastal-plain (White, 1929; Blakey, 1980); marine affinities suggested by Baars (1962).
Nodular to bedded aphanitic limestone (not shown on figure 8)	Micrite and nodular laminated to crinkly micrite laminated to structureless. Beds generally less than 0.5 m thick; nodules commonly 1-2 cm in diameter, beds rarely more than 1m thick. Associated with fine-grained facies; source of pebbles in coarse-grained facies.	Nodules formed as caliche in flood-basin soils; beds may represent calcretes or ephemeral pond deposits.
Flat-bedded sandstone and mudstone (fsm)	Sandstone, reddish-brown to yellowish, calcareous, wavy laminated to structureless to faintly cross-stratified; and mudstone, reddish-brown, thin, poorly exposed. Widespread in northwestern Arizona in Hermit-Queantoweap transition or facies change (Johansen, 1981).	Origin not well understood. May represent eolian sand-flat deposits and fluvial deposits near margin of Queantoweap sand sea.
Schnebly Hill Formation and DeChelly Sandstone (Leonardian)		
Cross-stratified sandstone (cs)	Quartz arenite, very fine to fine-grained, moderately to well-sorted; cross-stratified, mostly large scale with planar-tubular, planar-wedge, trough, and compound types. Sets up to 15 m thick, largest consistently dip SW-SE. Sandflow toes and inversely graded thin laminae locally to regionally abundant. Detailed descriptions and distribution provided by Blakey (1984), Blakey and Middleton (1983), and Vonderhaar (1986).	Rancho Rojo member interpreted as marine sand-wave complex by Blakey (1984). White House and Sycamore Pass members chiefly eolian (Peirce, 1964, 1966; Vonderhaar, 1986; Blakey and Middleton, 1984). Sycamore Pass contains intercalated shallow-marine deposits.
Wavy to ripple-bedded sandstone (wrb)	Quartz arenite and siltstone, slightly feldspathic, reddish-brown. Sedimentary structures include ripple lamination, wispy lamination, local wavy bedding; salt-crystal casts, and possible flaser bedding; minor small-scale trough cross-stratification. Prominent parallel horizontal erosion surfaces form beds 1-2 m thick	Based on sedimentary structures, stratigraphic position, and intercalation with other facies, much of facies formed on arid, low-energy coastal plain (Blakey and Middleton, 1983; Blakey, 1984).
Sandy mudstone (sm)	Mudstone, locally ripple bedded, locally calcareous to gypsiferous, sandy, poorly exposed, lacks channeling; reddish brown to reddish orange.	Probably lower energy parts of arid coastal plain. Not very well studied.
Aphanitic limestone and dolomite (ald)	Limestone, brownish-gray, micritic, silty, with molluscan fauna; chiefly fossiliferous wackestone (Gerrard, 1969). Dolomite, pinkish-gray to yellowish-gray, dense, silty, vuggy, crinkly laminations, intraformational brecciation; mostly dolomitic mudstone. Limestone percentage increases to southeast.	Low-energy carbonate shelf and restricted carbonate shoreline. Formed when maximum sea-level rise was coupled with low influx of siliciclastic debris.
Bedded evaporite (g)	Bedded gypsum, halite, and potash; locally form continuous strata 148 m thick (Peirce and Gerrard, 1966). Should not be confused or correlated with Wolfcampian evaporites.	Structurally restricted evaporite basin (Peirce and Gerrard, 1966). Probably continental to coastal sabkha in which evaporative accumulation matched rate of subsidence (Blakey, 1980).

TABLE 1. Facies description and interpretation. (Continued)

Facies	Description	Interpretation
Coconino and Glorieta Sandstone (Leonardian)		
Cross-stratified sandstone (cs)	Quartz arenite, very fine to medium-grained, well-rounded, noncalcareous. Large-scale cross-stratification dominated by planar-tabular and planar-wedge sets. Cross-strata dip southeast. Sandflow and grain-fall strata pass tangentially near base of set into nearly horizontal beds. Only facies recognized in Coconino and Glorieta Sandstones.	Eolian (McKee, 1979; Blakey and Middleton, 1983). Thinner sets eastward along Mogollon Rim may contain some waterlain strata (Peirce and others 1977). Cursory examination at several locations suggests thinner sets may be due to lower angle of bedform climb rather than change in environment.
Toroweap Formation (Leonardian)		
Skeletal to peloidal limestone (spl)	Skeletal packstone, skeletal wackestone, pelletal wackestone (Rawson and Turner-Peterson, 1980) and minor oolitic grainstone (Altany, 1979). Locally includes aphanitic carbonate. Beds horizontal to wavy bedded, locally stromatolitic, 5-7 cm thick (Rawson and Turner-Peterson, 1980).	Broad carbonate shelf with open-marine (skeletal and oolitic rocks) and restricted-marine (mudstones) conditions (Altany, 1979; Rawson and Turner-Peterson, 1980).
Sandy dolostone (sd)	Dolostone, silt-size rhombohedrons, with quartz sand.	Restricted-marine carbonate shoreline (Rawson and Turner-Peterson, 1980).
Red mudstone and sandstone (rms)	Sandstone, medium- to coarse-grained, quartz with minor feldspar grains, bimodally sorted; calcareous, gypsiferous, with interbedded red mudstone. Sedimentary structures include horizontal bedding, contorted bedding, ripple marks, local channels (Rawson and Turner-Peterson, 1980).	Coastal and continental sabkha complex; grades into and intercalated with supratidal gypsum (Rawson and Turner-Peterson, 1980).
Bedded gypsum (g)	Gypsum, nodular and laminated, typically contorted; contains abundant intercalated thin dolomite; abundant intraformational breccia (Rawson and Turner-Peterson, 1980; Altany, 1979).	Coastal sabkha (Rawson and Turner-Peterson, 1980; Altany, 1979).
Kaibab Formation (upper Leonardian)		
Skeletal limestone and dolomite (sld)	Skeletal packstone and wackestone, locally very cherty, peloidal, tannish-gray. Prominent horizontal bedding planes form beds up to several meters thick; sedimentary structures rare to lacking (Cheevers and Rawson, 1979).	Moderate-energy carbonate shelf; carbonate sand and mud formed in near proximity to one another; dominant facies during times of maximum transgression (Cheevers and Rawson, 1979).
Kaibab Formation (upper Leonardian)		
Dolomitic mudstone (dm)	Dolomitic mudstone, carbonate grains minor or absent, locally cherty; fine-grained texture consists of anhedral to subhedral dolomite crystals 4-35 microns. Terrigenous sand content ranges from near zero to over 50% (Cheevers and Rawson, 1979).	Low-energy to restricted carbonate shelf (Cheevers and Rawson, 1979).
Sandstone (ss)	Sandstone, quartz, very fine to fine-grained, unimodal to bimodal; dolomitic to calcitic cement; locally cross-stratified (Cheevers and Rawson, 1979).	Reworked Coconino (or White Rim in southern Utah) and (or) intertonguing with Coconino (White Rim). Probably shoreline and eolian deposits (Cheevers and Rawson, 1979).
Bedded gypsum (g)	Bedded gypsum, similar to that of Toroweap Formation.	Supratidal sabkha (Cheevers and Rawson, 1979).
Red sandstone and mudstone (rsm)	Similar to that of other previously described redbed facies.	Not well known; probably tidal-flat to broad coastal-plain.
Black Prince Limestone (Morrowan-Atokan)		
Maroon mudstone and shale (ms)	Mudstone and shale, rare coarser clastics; mottled with thin interbeds of pinkish and burrowed micritic limestone. Contains fragmental chert and reworked silicified fossils.	Basal deposit is reworked lateritic residuum formed on top of Escabrosa Limestone (Ross, 1973). Basal transgression of Pennsylvania seas over much of southeastern Arizona. Other thinner beds may represent brief subaerial exposure and pedogenesis.
Shelly calcarenitic limestone (sc)	Calcarenite, shelly, thin-bedded, locally displays tabular-planar cross-stratification (Knepp, unpub. data). Interbedded with micritic limestone. Abundant brachipod and echinoderm fragments, algal biscuits.	Shallow subtidal and intertidal deposition (Ross, 1973). Current bedding structures may indicate tidal or shoal-water reworking of deposits on shallow shelf.
Micritic limestone (ml)	Micritic limestone, thin-bedded to massive, sparsely fossiliferous except for calcarenite layers rich in shelly material; partially dolomitized, locally silty or clayey. Nodular chert distributed throughout, more abundant in shelly layers. Some bedding planes irregular, stylolitized, or marked by clay scans. Ross (1973) reported locally important intraformational conglomerate (calcirudites) associated with the micritic limestone. Brecciation and solution features occur locally.	Shallow subtidal deposits (Ross, 1973) with sporadic local exposure resulting in minor dolomitization, brecciation of supratidal deposits, and formation of syndepositional conglomerates.

TABLE I. Facies description and interpretation. (Continued)

Facies	Description	Interpretation
Horquilla Limestone (Lower) (Morrowan-Desmoinesian)—Facies I (see figs. 8, 10).		
Terrigenous Mudstone	Mudstone, olive-green and rare maroon terrigenous. Beds a few tens of cm up to several meters thick, forms covered slope. Tops usually gradational with overlying limestone; generally unfossiliferous; contact is heavily burrowed.	Initial transgressive deposits in cycles, similar to basal clastics in Orogrande Basin cycles (Wilson, 1967).
Cross-stratified silty mudstone and wackestone	Lime mudstone and wackestone containing 5% to 40% quartz silt, thick-bedded to massive, light-gray; silt weathers out in laminae and cross-laminae. Frequently burrowed, amount of burrowing inversely proportional to silt content. Fragmented crinoid columnals and bryozoan fragments; some mollusks, solitary corals, and brachiopods. Some partial dolomitization and neomorphism.	Open-shelf, well-oxygenated silt and traction structures probably from longshore transport; silt probably from Supai Group depositional basin (see Blakey, 1980, figs. 11-16).
Cherty mudstone and wackestone	Lime mudstone and wackestone, dark-gray irregular chert lenses, some pseudobeds up to 20 cm thick. Limestone strongly bioturbated. Fossils include partially silicified crinoids, bryozoans, mollusks, and fuslinids; massive to thick-bedded.	Open-shelf environment, more quiet water than above.
Bioclastic grainstones	Bioclastic grainstone; lenticular to tabular; lenticularity increases up-section. Chiefly beds of crinoid columnals, coated algal grains, or fusulinid tests. More lenticular beds usually contain rounded intraclasts of coarse sand- to pebble-sized lime mudstone. Some beds trough cross-stratified.	Probably tongues of winnowed material extending from carbonate buildups at shelf edge, may be storm deposited. More lenticular units contain rip-ups of underlying mudstone; possibly indicative of distal tidal channels.
Silty mudstone and bioclastic wackestone	Mudstone and wackestone, gray, about 5-10% silt, laminated to thick-bedded; locally, displays lenticular (linsen) bedding. Some burrowing and dolomitization.	Nearshore sublittoral shelf deposits, silt derived from onshore source. Linsen bedding suggestive of tidal currents.
Slope-forming lime mudstone	Lime mudstone, silty (5 to 15%), light-gray. Silt content increases up-section; intercalated ledges of darker gray packstone and grainstone; local thin gypsum beds; gradational near top with silicified dolomitic algal laminate.	Subtidal and intertidal deposits; algal laminates supratidal.
Upper Horquilla (Desmoinesian-Virgilian)—Facies II-A		
Mudstone and skeletal-pelletal wackestone	Lime mudstone and skeletal to pelletal wackestone, light-gray, massive, bioturbated; rare terrigeneous material; coated algal grains common; some clumps and mats of syringoporid corals. Includes some beds of finely crystalline to aphanitic dolomite.	Sublittoral (carbonate-shelf) deposits.
Calcareous terrigenous mudstone-siltstone	Terrigenous mudstone, tan, gray, and reddish-brown, silt content increases up-section. Moderately fossiliferous, typically calcareous. Some small-scale ripple and ripple-trough cross-lamination; heavily bioturbated. Grades into fine- and very fine grained sandstone at contact with Earp Formation.	Distal siliciclastic shoreline deposits.
Bioclastic intraclastic grainstone	Grainstone, thin-bedded, laterally discontinuous, structureless. Chiefly phylloid algal fragments, crinoid debris, fusulinids, and intraclasts.	Origin uncertain; geometry and intraclasts seem to indicate tidal-channel origin.
Earp Formation (Virgilian-Wolfcampian) lower Earp, (Virigilian)—Facies II-B		
Fine- and very fine grained sandstone	Quartzose to hybrid sandstone, calcareous cement; laminated to thin-bedded with small-scale ripple and ripple-trough cross-lamination and starved ripples. Minor horizontal burrowing, rare abraded molluscan material. Occurs throughout Earp Formation.	Barrier-bar complex; coarser sandstone may be tidal-channel deposits. Rare beds with low-angle tabluar cross-bed sets are of strandline origin.
Silty dolomitic lime mudstone and calcareous siltstone	Lime mudstone and calcareous sandstone, silt and carbonate fractions subequal; burrowing common. Bedding visible on etched surface and in thin section. Pellets and relict peloidal grains make up small amount of carbonate fraction.	Origin unknown; perhaps interbedded siltstone and mudstone mixed by bioturbation.
Lime mudstone	Lime mudstone, pale-pink to grayish-white with local purplish-gray bioclastic wackestone. Massive to thick-bedded, commonly with bedding stylolitized planes; red silicified echinoid spines, and brachiopods common.	Deposits formed on open, well-oxygenated, carbonate shelf.

TABLE I. Facies description and interpretation. (Continued)

Facies	Description	Interpretation
Earp Formation (Virgilian-Wolfcampian) Lower Earp, (Virigilian)—Facies II-B		
Calcareous terrigenous mudstone	Terrigenous mudstone, light-gray and light-green, calcareous. Laminated to thin-bedded, with lime-mud-filled burrows. Grades vertically into fine-grained sandstones.	Back-bar, protected nearshore deposits.
Upper Earp (Virgilian? and Wolfcampian)		
Chert- and limestone-pebble conglomerate	Conglomerate, red and tan chert and limestone pebbles and cobbles. Trough cross-bedded; forms lenticular laterally discontinuous bodies, grades laterally and vertically into sandstone and pebbly sandstone.	Origin enigmatic. May be of tidal-channel origin or representative of braided-stream deposition on an exposed shelf.
Claystones and marl	Claystone, pale-green, pinkish-white and light-gray; highly calcareous. Reddish siltstone common at base; typically grades vertically into fine-grained quartz sandstone.	Transgressive basal deposits of siliciclastic shoreline; offshore (sublittoral) mud and silt.
"Mini carbonate cycles"	Lime mudstone, light-gray, grades vertically into partially silicified yellow-brown aphanitic dolomitic algal laminate; uppermost few cm siliceous, some nodular chert.	Thin, shoaling-upward carbonate-shelf sequences from carbonate-shelf mudstone to supratidal dolomitized algal laminite and intraclastic mudstone.
Microsparitic wackestone	Wackestone, medium- to dark-gray, weathers light gray. Clay seams and discontinuous stylolites. Allochems consist of molluscan fragments and pellets, some phylloid algal fragments. Matrix microsparitic with minor silicification.	Tongues of overlying Colina Limestone, deeper water carbonate-shelf deposits. Replaces shoaling-upward sequences at top of section.
Colina Limestone and Epitaph Dolomite		
Skeletal limestone (sls)	Limestone, gray, fossiliferous, with unabraded and bioclastic grains that include brachiopods, bryozoans, echinoids, pelecypods, and gastropods (Butler, 1971; Wilt, 1969). Forms Colina Limestone	Shallow-marine shelf, subtidal to south, intertidal to north (Butler, 1971).
Dolomite (d)	Dolomite, argillaceous, carbonaceous; intraformational breccia. Low faunal diversity (Butler, 1971).	Partly a chemical facies of Colina. Associated with sabkha-supratidal deposition.
Redbeds and evaporites (re)	Red siltstone and mudstone and bedded gypsum.	Enigmatic. Facies suggest supratidal and sabkha conditions but distribution is in area of thickest Colina-Epitaph and surrounded by carbonate-shelf deposits.
Scherrer Formation (Leonardian)		
Basal redbeds (rms)	Siltstone and sandstone, slope-forming, thin-bedded; local ripple cross-laminations and scour-and-fill structures. Upper 8 cm consists of gray and pink limestone and dolomite at type locality (Luepke, 1971). The redbeds are regionally persistent (Bryant, 1968).	Environment uncertain; possibly distal deposits of a prograding clastic marginal-marine system.
Ortho-quartzite and calcareous quartz arenite (lss)	Quarz arenite, fine- to medium-grained, well-sorted, well-rounded, white, pinkish-orange, and light-gray. Butler (1971) reports tabular-planar cross-bedding; Luepke (1971) found no sets greater than 4 ft in thickness.	Unclassified marginal-marine sand bodies. Butler (1971) suggested an intertidal origin. The absence further south and west of the sandstone-carbonate-sandstone sequence was attributed by Bryant (1968) to thinning of the carbonate but is here believed more indicative of failure of the upper sand body to reach those areas.
Dolomite and micritic limestone (ml)	Dolomite and micritic limestone, varicolored, thin- to medium-bedded; 47 m thick at type section. Dolomite at base, micritic limestone in upper part. Abundant echinoid spines in limestone; "ghost" gastropods occur in dolomite. Micrite pink, gray, red, brown, and intermediate hues; sandy or silty, commonly displays dismicrite structures. Dolomite various shades of gray, slightly sandy. Carbonates locally cherty.	Shallow carbonate mudflat with sporadic subaerial exposure (Luepke, 1971). Where upper sandstone body missing, probably grades into shelf carbonates of Concha Limestone.
Concha Limestone (Leonardian-Guadalupian?)		
Cherty fossiliferous limestone (cfl)	Limestone, cherty, fossiliferous, medium- to dark-gray, cliff-forming; thick-bedded to massive. Chert light-gray, red, brown, white, or black. Chert locally constitutes 60% or more of some horizons. Dolomitization occurs only at base, limestone generally lacks clastic detritus. Upper portion of section may form ledge-and-slope or dip-slope topography (Bryant and McClymonds, 1961) gradational with underlying Sherrer Formation and overlying Rainvalley Formation.	Open carbonate-shelf, quiet-water environment (Butler, 1971).

TABLE 1. Facies description and interpretation. (Continued)

Facies	Description	Interpretation
Rainvalley Formation (Guadalupian)		
Quartz arenite	Light-gray to pale-red, horizontally laminated. Calcite cement, fine- to medium-grained; sub- to well-rounded (Vaag, 1984).	Vaag (1984) suggested sand blown from an onshore source and deposited without current rent or wave reworking.
Laminated micritic limestone	Alternation of light- and dark-gray, with grayish red replacing light-gray; some dolomitic horizons. Algal laminations common, some birdseye structures and desiccation cracks (Vaag, 1984).	Vaag (1984) interpreted this facies as intertidal to lower supratidal deposits with intermittent subaerial exposure.
Fossiliferous micritic	Various shades of gray and brownish or reddish gray; small amounts of quartz silt and sand included. Bioclasts include fragmented to whole mollusks, brachiopods, crinoids, and echinoids; fossil content ranges from sparse to packed.	Shallow subtidal to intertidal deposition (Vaag, 1984).
Peloidal micritic limestone	Gray and brownish-gray, some grayish-red, mottled; abundant quartz silt, authigenic quartz crystals, calcite-filled vugs. Horizontal burrows to pervasively bioturbated; birdseye structures. Pellets most abundant allochem, some molluscan and brachiopod fossils (Vaag, 1984).	Intertidal and some supratidal deposition under restricted circulation, variable salinity, and low energy (Vaag, 1984).

with the overlying Hermit varies. In some areas it is a sharp disconformity, and cross-stratified sandstone is abruptly succeeded by redbeds. Elsewhere the contact is gradational and probably intertonguing. Based on descriptions from Grand Canyon (McKee, 1982) and the Mogollon Rim (McAllen, 1984), six facies are recognized in the formation (table 1).

Queantoweap Sandstone. The Queantoweap Sandstone (McNair, 1951) is recognized in extreme northwestern Arizona and adjacent areas. Part of the formation is direct Esplanade equivalent. However, in extreme northwestern Arizona along the Virgin River Gorge the Queantoweap probably includes younger rocks, likely Hermit equivalents (Johansen, 1981). Facies are similar to those of the Esplanade.

Pakoon Limestone. The Pakoon Limestone intertongues with and gradually replaces the lower portion of the Esplanade Sandstone (McKee, 1982). Named by McNair (1951), the Pakoon comprises chiefly dolostone and bioclastic limestone with subordinate conglomerate, hybrid sandstone, gypsum, and red mudstone (McKee and Pierce, 1982). Throughout most of its extent in northwestern Arizona, it ranges from 100-150 m thick.

The Pakoon yields a rich Wolfcampian fauna described by McKee (1982). The Pakoon unconformably overlies the Wescogame Formation (or upper Callville Limestone of previous usage) and grades into the overlying Esplanade or Queantoweap.

Cutler Group

The Cutler Formation was raised to group status by Wengerd and Matheny (1958). At Monument Valley, four formations form the Cutler Group: Halgaito Formation, Cedar Mesa Sandstone, Organ Rock Formation, and De Chelly Sandstone (Baars, 1962). Northeastward, all four grade laterally into arkosic sandstone and conglomerate of the Cutler Formation. Although generally unfossiliferous, stratigraphic position and regional correlation firmly date the group as Wolfcampian and Leonardian (Baars, 1962; Blakey, 1980).

Halgaito Formation. The Halgaito Formation (formerly a member of the Cutler Formation; Baker and Reeside, 1929) disconformably overlies the Hermosa Group or Formation throughout much of the Four Corners region. The formation comprises red mudstone and sandstone and thin beds of aphanitic limestone and dolomite. Along the Colorado River in southeastern Utah, the Halgaito intertongues with carbonates of the Elephant Canyon Formation (Baars, 1962, fig. 3). It grades upward into the Cedar Mesa Sandstone and is apparently coeval with the lower Esplanade Sandstone (fig. 8). Intertonguing with the firmly dated Elephant Canyon Formation and stratigraphic position establish a lower Wolfcampian age for the Halgaito (Baars, 1962), although Loope (1984) has suggested that relations are more complex than previously thought.

Cedar Mesa Sandstone. The Cedar Mesa Sandstone, formerly a member of the Cutler Formation, was named by Baker and Reeside (1929) for exposures along the San Juan River at Cedar Mesa, about 35 km north of the Arizona border on the Monument Upwarp. Exposures in Arizona are limited to Monument Valley where a rather spectacular facies change occurs. Northward toward the San Juan River, the Cedar Mesa comprises chiefly cross-stratified sandstone; in less than 15 km the formation becomes chiefly reddish-orange sandy siltstone and mudstone, thin-bedded, crinkly laminated aphanitic limestone, and bedded gypsum, with subordinate cross-stratified sandstone. Numerous cyclic intercalations of the four above lithologies occur astride the Utah-Arizona state line in Monument Valley. Westward in the subsurface between Monument Valley and Grand Canyon, cross-stratified sandstone dominates the Cedar Mesa (Irwin and others, 1971; Baars, 1962); exposures in Grand and Marble Canyons are assigned to the Esplanade Sandstone.

Organ Rock Formation. The Organ Rock Formation (formerly member of Cutler Formation) was named for exposures in Monument Valley at Organ Rock (Baker and Reeside, 1929). It is lithologically similar to the Halgaito and has not been studied in enough detail to warrant facies analysis beyond what is shown on figure 8. Where separated from other units by overlying and underlying quartz sandstone, the Organ Rock forms a distinctive redbed sequence that was deposited across all of northern Arizona (figs. 6, 8). The southern and western portions of this sheet form the Hermit Formation (Baars, 1962; Blakey, 1979b, 1980). Southeastward of Monument Valley, the underlying Cedar Mesa Sandstone is absent and the Organ Rock is inseparable from underlying Halgaito (fig. 8; Read and Wanek, 1961; Baars, 1962).

The Organ Rock Formation is probably Leonardian. White (1929) assigned a Lower Permian, probably Leonardian age to the laterally equivalent Hermit Formation based on abundant fossil flora.

De Chelly Sandstone. The De Chelly Sandstone was named by Gregory (1917) for exposures of cliff-forming sandstone in Canyon De Chelly (pronounced deSha-y) on the Defiance Upwarp. Though chiefly cross-stratified sandstone, the De Chelly contains several other important facies and displays several rapid and extreme facies changes that have led to heated debates concerning Permian stratigraphy and nomenclature. Baars (1962) believed that the De Chelly was part of a widespread deposit that covered most of northeastern and east-central Arizona and parts of adjacent states, whereas Peirce (1964, 1967) considered the formation restricted to the Monument and Defiance Upwarps. Blakey (1979b) reviewed the problem and revised lower Leonardian stratigraphy in the region, the chief revision being the establishment and definition of the Schnebly Hill Formation in the Mogollon Rim. In Arizona, the De Chelly is herein recognized across the Monument and Defiance Upwarps and adjacent subsurface. It grades southwestward in the subsurface into basinal deposits of the Schnebly Hill Formation in the Holbrook Basin (Blakey, 1980, fig. 9; see figures 6, 8 of present paper). This correlation is briefly reviewed later in this paper. The De Chelly thickens southward from a zero edge along the San Juan River to over 250 m thick in Canyon De Chelly. Its age is middle Leonardian, based on stratigraphic position and relations to fossiliferous strata in the Schnebly Hill Formation. Distribution and lithology of three recognized members are shown on figure 8 and table 1.

Glorieta Sandstone

Peirce (1964, 1967) assigned cliff- and ledge-forming cross-stratified sandstone that conformably succeeded either the White House or Oak Springs Member of the De Chelly Sandstone to the Black Creek Sandstone Member of the De Chelly Sandstone. To emphasize regional correlation and relations between the De Chelly and younger though similar sandstone formations, the Black Creek Sandstone of Peirce is included in the Glorieta Sandstone. This conforms with correlation and usage of Read and Wanek (1961) and Baars (1962). The Glorieta is present in Arizona only on the southern and eastern Defiance Upwarp and adjacent subsurface. The same sandstone sheet exposed on the

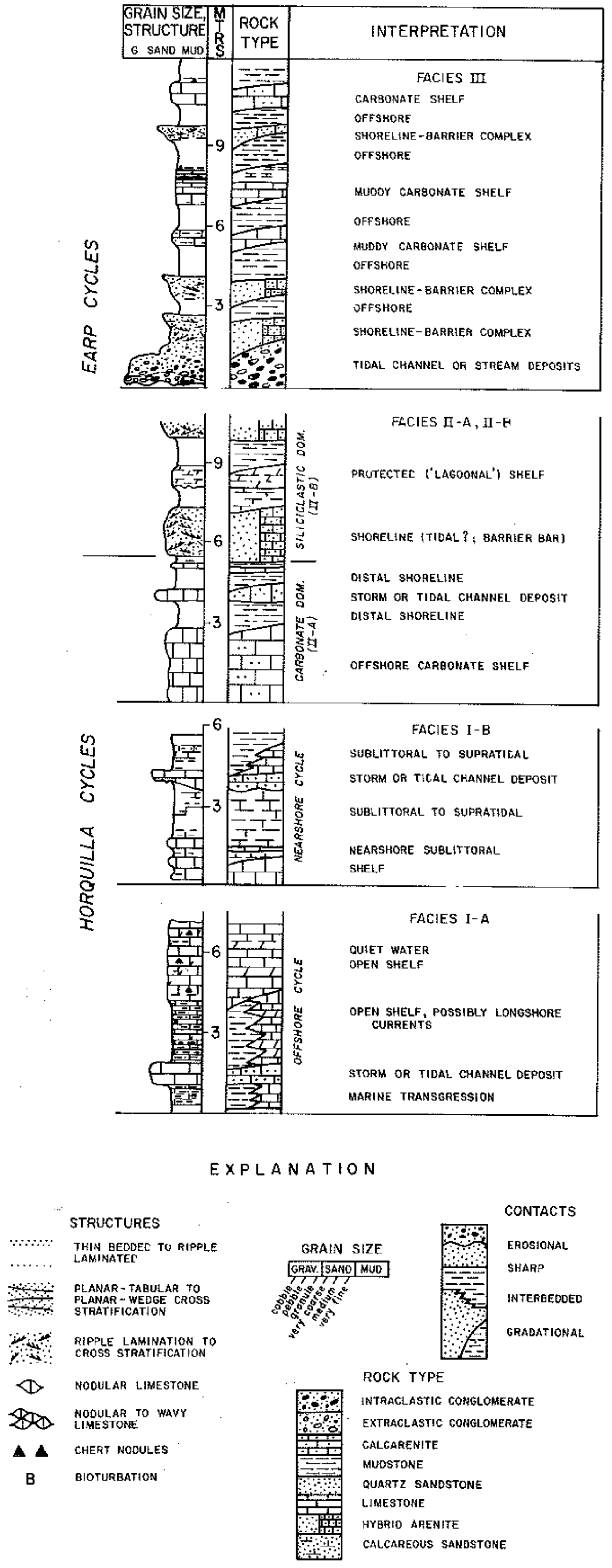


Figure 10. Detailed partial lithologic logs of Horquilla and Earp Formations, central Cochise County, showing representative examples of each cyclic facies in table 1. Logs arranged in general order (oldest at base) from lower Horquilla to upper Earp.

Mogollon Rim is the Coconino Sandstone (figs. 6, 7, 8). The Glorieta consists of variably thick sets of cross-stratified quartz sandstone; it thickens to the southeast (fig. 8).

Stratigraphic position firmly establishes an upper Leonardian age for the Glorieta Sandstone (Baars, 1962). All of the Glorieta sandstone in Arizona is assigned to the cross-stratified facies (fig. 8).

Beds at Fort Defiance

The removal of the Glorieta (Black Creek) Sandstone from the De Chelly Sandstone leaves several tens of meters of overlying strata presently unassigned. Peirce (1964, 1967) assigned the rocks in question to the Fort Defiance Member of the De Chelly Sandstone. Pending further study, we prefer to leave the unit unassigned and refer to it informally as the beds at Fort Defiance (fig. 8). As described by Peirce (1964, 1967) the unit consists of slope-forming, flat-bedded siltstone and sandstone up to 30 m thick. The unit is present only in the Fort Defiance area. Age and correlation of these strata are unknown. Possibilities include (1) local clastic facies of the Permian Kaibab-San Andres Formations (Baars, 1962), (2) Lower Triassic Moenkopi equivalent, or (3) local Permian or Triassic unit not directly related to either of above.

Hermit Formation

The Hermit Formation was named by Noble (1922) for exposures in the Hermit Basin near Grand Canyon Village. Though originally referred to as shale by earlier workers, the term formation better reflects its complex heterolithic nature. The formation comprises red mudstone, siltstone, flat-bedded, ripple-laminated, and cross-stratified sandstone, aphanitic limestone, and sedimentary-pebble conglomerate. Based on careful stratigraphic work, Blakey (1979b, 1980) extended the Hermit into the Mogollon Rim region (figs. 6, 8). As recognized herein, the Hermit is part of the most extensive Pennsylvanian-Permian stratigraphic sequence of the southwest. The Hermit itself forms a thin sheet of redbeds 30-100 m thick in eastern Grand Canyon and throughout the Mogollon Rim and thickens to over 300 m in western Grand Canyon. The overall redbed sheet is present south of a line from Moab, Utah, to the Virgin Mountains and includes the Hermit in Grand Canyon and the Mogollon Rim, the Organ Rock in southeastern Utah and northeastern Arizona, the Abo Formation in western New Mexico, the middle and upper Earp Formation in southeastern Arizona, and possibly unnamed Permian redbeds in the upper plate of the Keystone Thrust in the Spring Mountains of southern Nevada (fig. 6).

Contact with underlying Earp Formation where the Esplanade is absent is unconformable and marked by extensive conglomerate. Contact with overlying Coconino Sandstone or Schnebly Hill Formation is always sharp, and lacks any evidence of either gradation or channeling.

Four facies are described in table 1, although regional distribution of each is poorly known and only generally depicted on figure 8. Age of the Hermit based on stratigraphic position and well-studied flora (White, 1929) is Wolfcampian to Leonardian.

Schnebly Hill Formation

The Schnebly Hill Formation (Blakey, 1979a, 1979b, 1980) was named for towering reddish-orange cliffs and slickrock country in and around Sedona along the west-central Mogollon Rim. Originally considered part of the Supai Formation (McKee, 1945; Huddle and Dobrovolny, 1945), the Schnebly Hill contains a middle Leonardian fauna considerably younger than the type Supai; in addition, there are no rocks similar to the Schnebly Hill in Grand Canyon. Rather, the formation was deposited within and on the southern and southwestern margins of the Holbrook Basin. The formation is marked by sharp, clearly exposed facies changes and comprises cross-stratified, wavy to ripple-laminated, and plane-bedded sandstone; mudstone; generally aphanitic limestone and dolomite; and evaporites.

The Schnebly Hill thickens from a zero edge in the western Mogollon Rim and subsurface east of Grand Canyon to over 600 m in the Holbrook Basin. It sharply overlies the Hermit Formation and grades upward and commonly intertongues with the overlying Coconino. Eastward in New Mexico, the Schnebly Hill grades into the Yeso Formation (Wengerd, 1962; Baars, 1962). Across the Holbrook Basin it grades into the De Chelly Sandstone (Blakey, 1979b, 1980). The Fort Apache Member yields a Leonardian fauna (Winters, 1963; Ross, 1973) and Weisman (1986) reported a middle to middle late Leonardian conodont from a thin limestone bed above the Fort Apache Member near Fossil Creek.

Six members are recognized within the Schnebly Hill Formation; three are names retained from when the formation was considered part of the Supai Formation and three were proposed by Blakey (1979b, 1980). Distribution, lithology, and relation of the members are shown on figure 8 and table 1.

Correlation, both physical and temporal, of the Schnebly Hill Formation with the De Chelly Sandstone remains controversial. H. Wesley Peirce (personal commun., 1986) strongly feels that possibly none and at best only the top of the Schnebly Hill correlates with the De Chelly and that the latter represents a post-Schnebly Hill depositional sequence that is absent in the Mogollon Rim. He further postulates an unconformity between the Schnebly Hill and Coconino Sandstone in the Mogollon Rim that represents the De Chelly time interval. His evidence is chiefly based on correlation of thin carbonate horizons from the Mogollon Rim northward across the Holbrook Basin and onto the Defiance Upwarp (Peirce, 1967, his fig. 1). On the Mogollon Rim outcrops near Fort Apache, the carbonates lie near the top of the Corduroy Member of the Schnebly Hill Formation; on the south Defiance Upwarp, Peirce believes that one such thin carbonate underlies the entire De Chelly interval and hence demands that all but the uppermost Schnebly Hill is younger than the De Chelly.

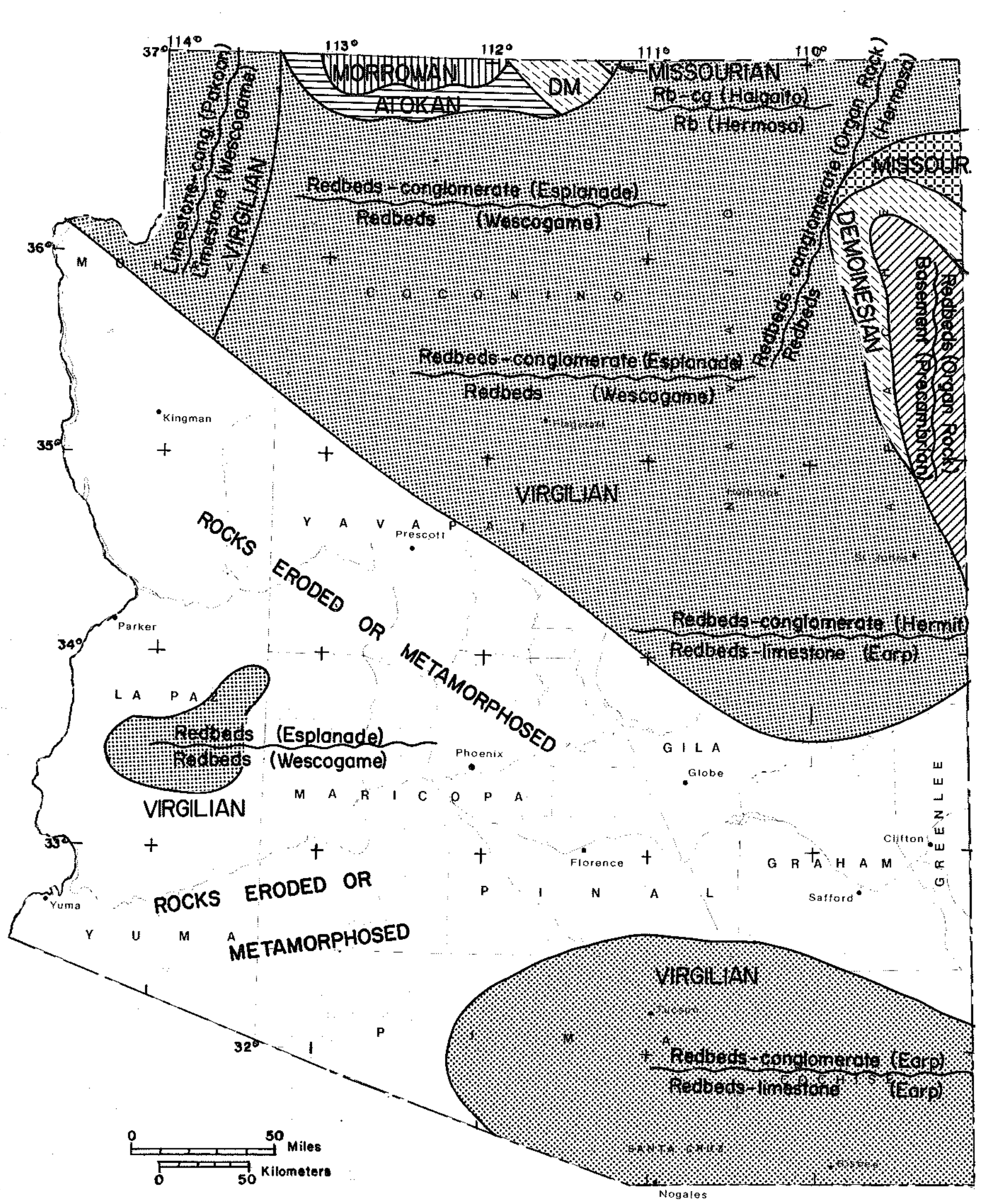


Figure 11. Map showing nature of Pennsylvanian-Permian boundary in Arizona. Wavy line at each location separates underlying and overlying lithologies and formations. Map patterns show approximate distribution of ages of rocks under the Permian system.

We present three separate lines of evidence that suggest that much of the Schnebly Hill and De Chelly are direct physical and partially temporal equivalents. We recognize that both Schnebly Hill and De Chelly facies are strongly time transgressive and that bed for bed or even member for member temporal correlation is difficult. Our evidence for correlating the Schnebly Hill and De Chelly follows:

1. The Schnebly Hill Formation is exposed as far north as Mt. Elden on the north edge of Flagstaff. Subsurface data demonstrates that red-orange quartz sandstone underlies the Coconino Sandstone at Sunset Crater National Monument (Paul Christenson, personal commun., 1982) and in the Cameron, Echo Cliffs, and northeastern Coconino County areas (Baars, 1962; Irwin and others, 1971; see also our figure 8c) and possibly outcrops east of Grand Canyon along the East Kaibab Monocline (Charles Barnes, personal commun., 1985). The oil test in northern Coconino County (fig. 1) is less than 40 km from outcrops of the De Chelly Sandstone in the Monument Valley area. We feel that this evidence strongly suggests that the De Chelly and Schnebly Hill form a continuous red-orange sandstone body that wraps around the northern and western edges of the Holbrook Basin.

2. Detailed sedimentologic and stratigraphic work in the Sedona area demonstrates conclusively that the stratigraphic boundary between the Schnebly Hill and Coconino is gradational and intertonguing and that no major unconformity is present in the Schnebly Hill-Coconino section. This would demand that De Chelly time is represented in the Mogollon Rim country (fig. 8d). Facies and sedimentologic data, combined with item 1 above, indicate that the Schnebly Hill interval contains the De Chelly equivalents.

3. Although Peirce (1967) clearly indicated that the above-mentioned key carbonate beds lie below the De Chelly Sandstone, Read and Wanek (1961) showed a different interpretation. Their Plate 2, sections 15 and 16 show carbonate beds well within the De Chelly interval; they correlated these beds into the Oak Springs Member of Peirce (1967). Read and Wanek also show the De Chelly to intertongue or gradationally overlie the Supai Formation (Organ Rock of this paper). Therefore, the relation of key carbonate beds on the southern Defiance Upwarp seems in doubt. If Read and Wanek are correct, the entire lower portion of the De Chelly Sandstone can have time equivalence with the Schnebly Hill Formation and need not be younger as Peirce insists. Work in progress by Blakey is attempting to confirm these relations.

We conclude that some and possibly most of the De Chelly Sandstone correlates physically and temporally with the Schnebly Hill. Together, these units comprise a sandstone sequence that rims the Holbrook Basin and interfingers with thick, coeval basinal deposits of the basin center.

Coconino Sandstone

The Coconino Sandstone was named for exposures on the Coconino Plateau in central Coconino County by Darton (1910). The cliff-forming, cross-stratified, nearly pure quartz arenite is widely exposed throughout northern Arizona. From a maximum thickness of over 300 m near Pine, Arizona, the formation thins and wedges out in the subsurface east of the Defiance Upwarp and south of Monument Valley and westward along the Arizona-Utah state line. In western Arizona, it maintains a thickness of less than 20 m into eastern Nevada. It is present in southwestern Arizona in the Plomosa Mountains and several other isolated locations. The Coconino sharply overlies the Hermit throughout Grand Canyon and intertongues into the Schnebly Hill Formation in the Mogollon Rim. West of a line from Sycamore Canyon to Page it intertongues with and is overlain by the Toroweap Formation (Rawson and Turner-Peterson, 1980). East of that line it is overlain by and possibly intertongues with the Kaibab Formation (Cheevers and Rawson, 1979). The Coconino thins and grades eastward into the Glorieta Sandstone of New Mexico (Baars, 1962). Though the Coconino is not known to contain time-sensitive fossils, based on stratigraphic position, its age is firmly established as middle Leonardian.

Toroweap Formation

The Toroweap Formation was separated from strata originally assigned to the Kaibab Formation by McKee (1938). Type section is near Toroweap Point in north-central Grand Canyon. Though predominantly limestone in many areas, the Toroweap contains appreciable amounts of yellow sandstone, red sandstone and mudstone, sandy dolomite, and gypsum (fig. 8). The Toroweap is present in northwestern Arizona west of a line from Sycamore Canyon to Page. East of this line it rapidly changes facies into the Coconino Sandstone (Rawson and Turner-Peterson, 1980) so that eastern outcrops of Coconino contain rocks of Toroweap age. Throughout most of its extent it maintains a thickness of 100-150 m. The formation conformably overlies and commonly intertongues with Coconino across much of northern Arizona and is unconformably overlain by the Kaibab Formation. The Toroweap is probably present in the Plomosa Mountains (Miller and McKee, 1971) but is difficult to separate from the Kaibab Formation.

The Toroweap, although locally fossiliferous, lacks fossils useful for precise dating and is assigned a middle to late Leonardian age based on stratigraphic position. Three members are recognized throughout most of its extent (fig. 8; table 1).

Kaibab Formation

The Kaibab Formation (Darton, 1910) was redefined by McKee (1938); type section is in Kaibab Gulch in southern Utah. Predominantly limestone and dolomite, the formation also contains sandstone, red sandy mudstone, bedded gypsum, conglomerate, and variable amounts and types of chert (McKee, 1938; Brown, 1969; Cheevers and Rawson, 1979). Because the resistant widespread Kaibab has formed an erosional strip plain several times in its postdepositional history, diagenesis has had profound effects on its lithologic character.

At one time the Kaibab probably covered much of northern Arizona, though at present the unit is absent across both the Defiance and Monument Upwarps and parts of the Little Colorado River valley. The Kaibab forms a broad tabular body that gradually thickens westward, ranging from 100-200 m thick except where removed by post-Permian erosion (fig. 8). It is also recognized in several scattered mountain ranges in southwestern Arizona, most notably the Plomosa Mountains (Miller and McKee, 1971). Both lower and upper contacts are sharp disconformities, although the lower contact is difficult to pick in several locations. At one time most of the Kaibab was unconformably overlain by the Moenkopi Formation, but post-Moenkopi erosion has removed the less resistant redbeds in many places and a variety of Tertiary volcanics and sediments now overlie the Kaibab. Where the Permo-Triassic unconformity is exposed, it is generally readily apparent from sharp color and lithologic change and local erosional relief of 10 or more meters. In northwestern Arizona and adjacent Utah the Kaibab is overlain by similar basal carbonate of the Moenkopi Formation, and more care is needed to distinguish the two formations (Blakey, 1979c; Nielson and Johnson, 1979).

A well-known marine fauna yields a latest Leonardian to earliest Guadalupian age for the Kaibab (McKee, 1938). Although McKee (1938) originally recognized three informal members within the Kaibab, most subsequent workers have more or less formalized two members and this terminology is used herein (fig. 8; table 1).

Naco Group

The Naco Group contains both Pennsylvanian and Permian strata in southeastern Arizona and Pennsylvanian strata in the Mogollon Rim (Ross, 1973). Permian strata in southeastern Arizona include the upper Earp Formation, Colina Limestone, Epitaph Dolomite, Scherrer Formation, Concha Limestone, and Rainvalley Formation. The Earp has already been discussed and will not be repeated here.

Colina Limestone and Epitaph Dolomite. Gilluly and others (1954) named the Colina Limestone, establishing a type section at Colina Ridge in the Tombstone Hills. Unlike the underlying Horquilla Limestone and Earp Formation, the Colina lacks well-developed cyclicity, comprising instead a relatively uniform sequence of thick-bedded dark-gray limestone (Bryant, 1968). Gilluly and others (1954) also established the name Epitaph Dolomite for a thick sequence of dolomite, fine red clastics, and limestone exposed on the dip slope of Colina Ridge. The contact between the two formations is of a chemical rather than sedimentological nature; it consists of an irregular dolomitization boundary, which is not confined to a given stratigraphic horizon. At the type section of the Colina and Epitaph, a given limestone bed can be traced physically from the Colina to its dolomitized equivalent in the Epitaph (Patch, 1969; Wilt, 1969). The two formations are typically treated as a single depositional unit (cf. Bryant, 1959; Butler, 1971), albeit a unit with complex internal sedimentologic relationships.

The Colina-Epitaph sequence overlies the Earp Formation with an intertonguing gradational contact, and is in turn conformably overlain by the Scherrer Formation (Gilluly and others, 1954). The sequence is of Wolfcampian? and Leonardian age; the Epitaph Dolomite facies is probably wholly of Leonardian age (Gilluly and others, 1954). The Colina shelf limestone facies is more widely distributed than the supratidal dolomite-clastic-evaporite facies of the Epitaph.

The limestones of the Colina generally thicken toward southeastern Arizona, from about 61 m in the Waterman Mountains northwest of Tucson (McClymonds, 1959) to approximately 305 m in the Pedregosa Mountains (Cooper, 1959). Local thickness variations of 30 to 61 m result from the irregularity of the Colina-Epitaph dolomitization boundary (Wilt, 1969). The Epitaph Dolomite facies has been mapped only at scattered localities, particularly on the western shelf of the Pedregosa Basin (i.e., Whetstone and Empire Mountains and Tombstone Hills). Its absence at other locations poses what is probably the major enigma of southeastern Arizona Paleozoic stratigraphy. Where present, the dolomite, fine clastics, limestone, and evaporite of the Epitaph range in thickness from 305 to 457 m; however, the absence of these strata is not offset by thickening of underlying or overlying strata. The enigmatic areal distribution of the Epitaph, the complex internal stratigraphy, and the uncertain depositional and tectonic setting of the Colina-Epitaph sequence are in need of in-depth research.

Scherrer Formation. The Leonardian Scherrer Formation was established by Gilluly and others (1954) for strata exposed at Scherrer Ridge in the Gunnison Hills. At the type section the formation consists of basal redbeds, lower sandstone, middle carbonate, and upper sandstone (Luepke, 1971). The Leonardian age of the Scherrer is based upon stratigraphic position: the only abundant fauna, echinoid spines, are not age specific. The Scherrer is present in mountain ranges throughout Cochise, Santa Cruz, and eastern Pima Counties and southwesternmost New Mexico. The Scherrer thins from 207 m at the type section (Luepke, 1971) to less than 7 m in the Big Hatchet Mountains (Zeller, 1965). The formation also thins to the west and southwest (Butler, 1971).

Carbonate and clastic beds of the underlying Epitaph Dolomite grade into the basal redbeds of the Scherrer, except at the type section, where Epitaph strata are absent (Gilluly and others, 1954). The contact with the overlying Concha Limestone is sharp. The quartz arenite-cherty limestone couplet observed in the Scherrer and Concha formations, when combined with their Leonardian age, has led workers to suggest correlation with similar, coeval Coconino-Kaibab and Glorieta-San Andres combinations of the Colorado Plateau and central and southern New Mexico, respectively (Knepp, 1983).

Concha Limestone. Gilluly and others (1954) named the Concha Limestone for about 40 m of cherty fossiliferous limestone exposed at Concha Ridge in the Gunnison Hills. Bryant and McClymonds (1961) described a reference section 174 m thick in the Mustang mountains, where the formation is overlain by the Rainvalley Formation. At most locations, sandstone of the underlying Scherrer Formation changes abruptly into sandy and silty limestone or dolomitic limestone of the Concha. The upper contact is a gradation into thin-bedded black limestone of the Rainvalley Formation (Bryant and McClymonds, 1961).

The age of the Concha is well established as Leonardian (Sabins and Ross, 1965) and Guadalupian (Vaag, 1984). The Concha crops out in ranges throughout southeastern Arizona and southwestern New Mexico, except where removed by post-Paleozoic erosion. Its thickness remains relatively constant at about 150 m in central and western Cochise County, but thins slightly to the west and southwest (Bryant and McClymonds, 1961).

Rainvalley Formation. Bryant and McClymonds (1961) established the Rainvalley Formation for about 120 m of limestone, dolomitic limestone, and sandstone exposed above the Concha Limestone in the Mustang Mountains. The Rainvalley gradationally overlies the Concha. The top of the Rainvalley is everywhere an erosion surface overlain by Cretaceous or Cenozoic strata with angular unconformity. The age of this formation is Guadalupian (Vaag, 1984), based upon stratigraphic position. It is probably laterally correlative with part of the Kaibab Limestone.

No complete section of the Rainvalley is known, so thickness trends are controlled only by post-Rainvalley erosion. The formation crops out in scattered mountain ranges in Cochise, eastern Pima, and northern Santa Cruz counties (Titley, 1976). Sabins and Ross (1965) reported 200 m of Concha Limestone in the Chiricahua Mountains, but failed to identify any Rainvalley Formation at that location.

GEOLOGIC HISTORY

Definition of Phase

The Pennsylvanian and Permian geologic history of Arizona is discussed within loosely defined episodes of time we call phases. A phase is a characteristic time or time-rock interval during which characteristic depositional systems were formed. The phases are nonquantitative periods of time, but they can be assigned within the various formal series of the Pennsylvanian and Permian (Morrowan, Wolfcampian, etc.). Thus relative ages of the proposed phases are fixed by regional stratigraphy and referred to the above series, but absolute fixed duration or assignment to a smaller subdivision of formal time-rock stratigraphy is undeterminable. A phase is a package of rock (or unconformity where rock is missing) with a given geometry; boundaries may be distinct or gradational. It may consist of single or multiple facies and single or multiple formations. A phase is therefore the product of geologic processes that operate in response to local and regional tectonics and changes in sea level. Phases are numbered consecutively by system, given descriptive names, and assigned to one or more formal series (fig. 6). Three Pennsylvanian and five Permian phases are recognized.

Pennsylvanian Phases of Deposition

1. *Lower Clastic and Carbonate Phase (Morrowan-Atokan).* This phase includes the Black Prince, lower Horquilla, lower Hermosa and Molas, and Watahomigi and Manakacha stratigraphic units (figs. 6, 12). It is represented by an unconformity across the eastern Sedona Arch and most of the Defiance Positive Area. It includes formats A and B of Ross (1973). The tri-basin pattern that dominated the Pennsylvanian is strongly developed (fig. 12).

Across northwestern Arizona including Grand Canyon, the basal conglomerate of the Watahomigi Formation contains a sparse marine fauna (McKee, 1982). This and other similar basal Pennsylvanian conglomerates formed, following long periods of weathering, on underlying Mississippian cherty carbonate (Merrill and Winar, 1958; Ross, 1973; Blakey, 1980). The conglomerate grades upwards into fine-grained redbeds and impure carbonate that formed on muddy coasts during basal transgression. Most of the Watahomigi carbonate is aphanitic and formed on a somewhat restricted, clear-water carbonate shelf (Blakey, 1980; McKee, 1982). In western Grand Canyon and the Virgin Mountains, accretal and mixed-grain limestone formed on a higher-energy shelf, possibly coincident with a shelf break, with deeper water to the west of Arizona (fig. 12). An increase in red fine-grained clastics and withdrawal of the sea led to development of a pre-Atokan unconformity (McKee, 1982). Another major cyclic incursion of the sea into northwestern Arizona, accompanied by influx of quartz sand from the north, formed the Manakacha Formation in Atokan time. Marine sand waves and megaripples migrated southward across the Grand Canyon Embayment (McKee and Pierce, 1982). Bedforms farther west were dominated by carbonate grains; quartz sand content increased towards central and eastern Grand Canyon. Detailed studies of the Manakacha in the western Mogollon Rim document at least eight transgressive-regressive cycles (fig. 9). Work in progress but not yet published strongly suggests that some cross-stratified sandstone units in the Supai Group are of eolian origin. This work will undoubtedly alter some of the interpretations offered herein.

This phase is represented by the pre-Desmoinesian unconformity across east-central Arizona. However, Atokan and possibly Morrowan rocks are known from the subsurface of extreme northeastern Arizona (Wengerd and Matheny, 1958). Little is known about their depositional history, but extrapolated from probably similar rocks in southwestern Colorado (Merrill and Winar, 1958), basal Pennsylvanian strata of the Molas Formation accumulated as reworked karst material, followed by cyclic intercalations of shallow marine, coastal plain, and fluvial deposits.

In southeastern Arizona, the Morrowan Black Prince Limestone contains basal conglomerate and mudstone overlain by nearly pure limestone deposited in a clear, warm sea. Calcarenitic limestone formed as shoals near shelf breaks or during periods of higher energy associated with transgression and regression, and micritic limestone formed in deeper water or protected shallow areas (Ross, 1973). Local intraformational conglomerate and breccia and associated thin dolostone probably formed on coastal plains during a minor hiatus following regression. Following the last withdrawal of the Morrowan sea, a major unconformity developed on the surface of the Black Prince Limestone (Ross, 1973, p. 897). Where the unconformity is most strongly developed, the Horquilla directly overlies Mississippian rocks. Following basal Atokan transgression, cyclic carbonate deposits were spread across much of southeastern Arizona. Deeper-water deposits are restricted to extreme southeastern Arizona and intercalated carbonate-bank or bioherm, low-energy shelf, and thin mudstone deposits formed elsewhere (Ross, 1973). Withdrawal of Atokan seas led to formation of a major unconformity in northwestern Arizona (McKee, 1982) and a relatively minor unconformity in northeastern and southeastern Arizona (Ross, 1973).

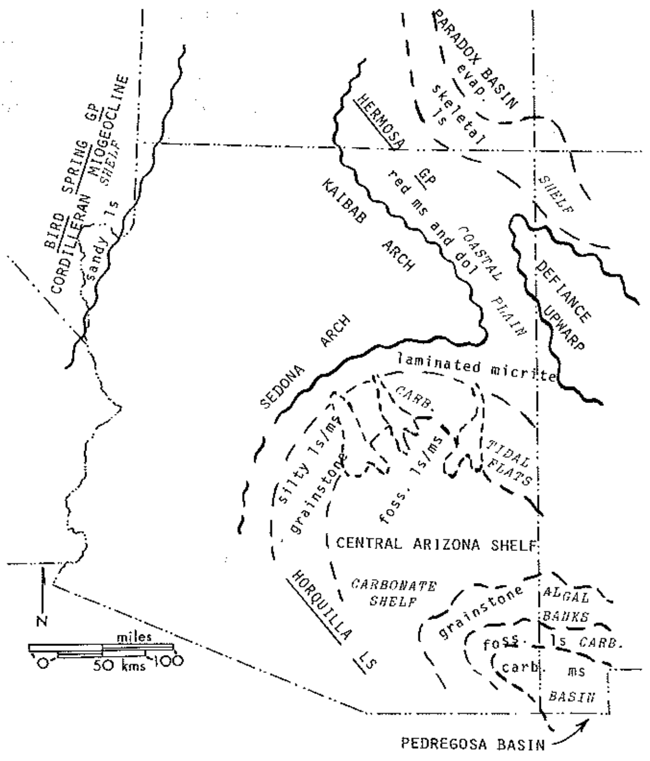


Figure 13. Generalized facies, tectonic elements, and hypothetical paleogeography during maximum Desmoinesian transgression of Pennsylvanian Phase II.

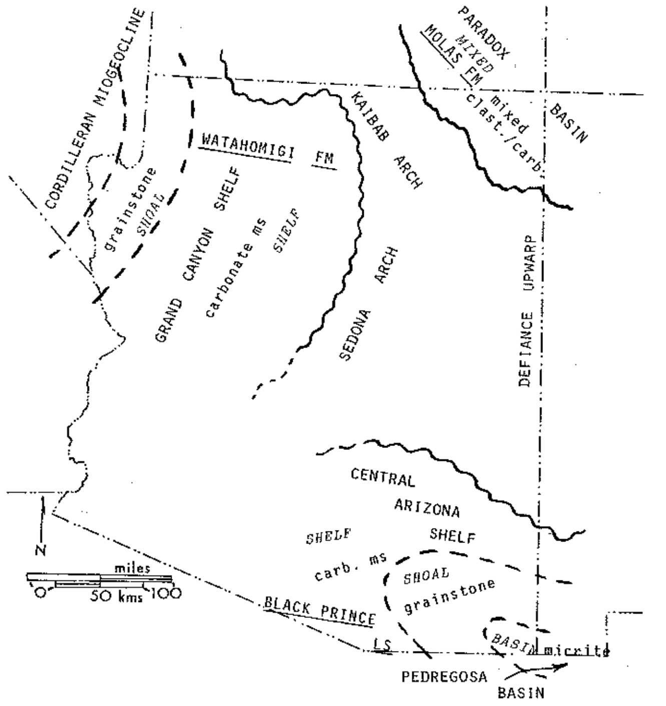


Figure 12. Generalized facies, tectonic elements, and hypothetical paleogeography during maximum Morrowan transgression of Pennsylvanian Phase I.

2. *Middle Carbonate Phase (Desmoinesian-Missourian).* This phase includes the Horquilla and Hermosa stratigraphic units and was deposited across much of Arizona east of the Sedona Arch (fig. 13). The phase is equivalent to format C-I of Ross (1973).

The sequence is absent throughout the Grand Canyon-western Mogollon Rim region where it is represented by a major unconformity between the Manakacha and Wescogame Formations (McKee, 1982). Welch (1959) reported thin fusulinid-bearing sandy carbonate of Desmoinesian age in the Virgin Mountains; Desmoinesian and Missourian strata are widespread in the Bird Spring Group of southern Nevada (Langenheim and Webster, 1979).

Northeastern Arizona was near the landward edge of a shelf adjacent to the Paradox Basin (fig. 13). Shallow-marine carbonates of Desmoinesian age are abundant along the state line east of Monument Valley but thin rapidly and grade southwestward into unfossiliferous redbeds (Pope, 1976). Transgressive-regressive sequences comprising carbonate-shelf, restricted carbonate-shelf, and coastal redbeds dominate Desmoinesian rocks (Pope, 1976). Missourian rocks include more clastics and probably formed on a low-lying coastal plain.

Along the eastern Mogollon Rim and in southeastern Arizona the middle carbonate phase is represented by the bulk of the Horquilla Limestone. Along the Mogollon Rim east of Fossil Creek and in northern parts of southeastern Arizona, basal Desmoinesian sediments include basal conglomerate and fine-grained terrigenous clastics deposited during initial transgression (Brew, 1965; Ross, 1973). Most of the Horquilla Limestone was formed by repeated transgression and regression of carbonate-producing seas. Knepp (1983) recognized two types of cycles in this part of the Horquilla (fig. 10). Lower outer-shelf cycles are interpreted as follows: (1) initial transgression represented by olive-green terrigenous mudstone; (2) well-oxygenated open shelf subjected to probable longshore currents, represented by sandy to silty carbonate mudstone and wackestone; (3) tidal-channel and (or) storm deposits represented by lenticular to tabular bioclastic crinoidal grainstones (position varies in cycle); and (4) open-shelf, quiet-water environment represented by bioturbated, fossiliferous cherty carbonate mudstone and wackestone (fig. 13). Upper nearshore cycles are interpreted as follows: (1) nearshore sublittoral and tidal-flat deposits represented by silty carbonate mudstone and wackestone; (2) subtidal, intertidal, and supratidal deposits represented by slope-forming lime mudstone and dolomitic algal laminite; and (3) tidal-channel and (or) storm deposits represented by lenticular to tabular bioclastic crinoidal grainstone (position varies in cycle).

A widespread period of erosion is documented by the pre-Missourian unconformity (unconformity 8 of Ross, 1973) across much of southeastern Arizona. Red siltstone and sandstone and scattered limestone-pebble conglomerate overlie the unconformity and formed by reworking of red lateritic soils following the middle Pennsylvanian regression (Ross, 1973). Ensuing carbonate-shelf deposition was similar to that of the Desmoinesian except that terrigenous clastic deposition became dominant in parts of the Mogollon Rim, and upper nearshore cycles of Knepp (1983) dominate sections in southeastern Arizona. A terrigenous coastal plain dominated sections in the Rim and shoreline and nearshore carbonate deposition took place to the south.

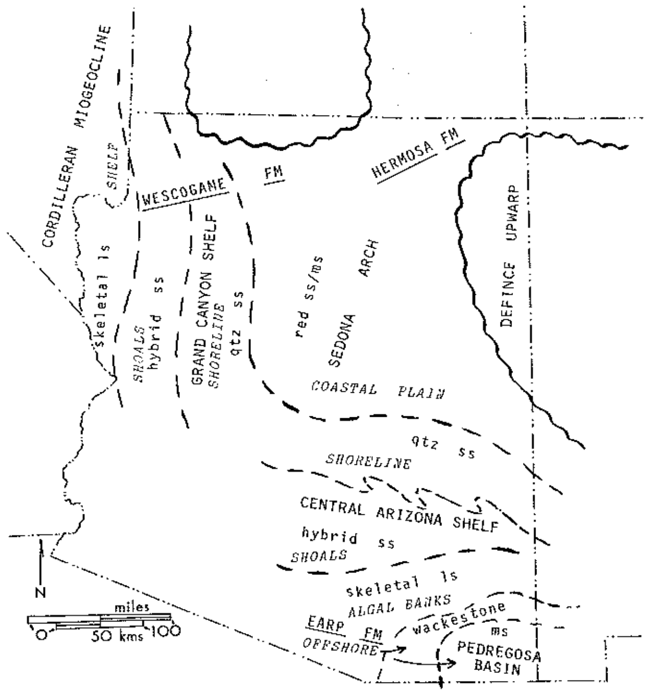


Figure 14. Generalized facies, tectonic elements, and hypothetical paleogeography during maximum Virgilian depositional extent of Pennsylvanian Phase III.

3. *Upper Redbed Phase (Virgilian).* This is the most widely distributed Pennsylvanian phase in Arizona (fig. 14). The Wescogame, upper Hermosa, and Earp lithologic units were deposited during this phase; in southeasternmost Arizona the uppermost Horquilla, formats J, K, and L of Ross (1973), is represented.

West of the Hurricane Cliffs the Wescogame is dominated by calcareous hybrid sandstone and skeletal limestone, which formed on high-energy shelf and open-marine carbonate shelf respectively (McKee and Pierce, 1982). Details of distribution and type of cycles formed by these two lithologies are poorly understood, especially in the Virgin Mountains. Farther east across most of Grand Canyon, cyclic redbeds and quartz arenite dominate the Wescogame. McKee (1982) suggested formation in estuarine and fluvial environments but details of depositional process were not provided. Work in progress by Blakey has documented an eolian origin for some of these units.

Along the western Mogollon Rim, detailed analysis of cycles suggests formation on a clastic shelf; cycles are similar to those of the Manakacha: marine sandwave or megaripple deposits are overlain by carbonate mudflat and redbed lagoonal or coastal-plain deposits. At least ten such cycles were noted (fig. 9). Northeast along the southern flank of the Paradox Basin, the uppermost Hermosa formed on a coastal plain. Details of depositional history are unknown.

Along the Mogollon Rim from Fossil Creek eastward, the Earp Formation comprises red sandy mudstone, very fine grained calcareous sandstone, and sandy dolostone. Although details of depositional processes are not known, the cyclic intercalation of the above lithologies suggests formation on sandy shelf and adjacent muddy coastal plain (fig. 14). Eastward along the Rim, the increase in sandy skeletal limestone suggests formation farther offshore on a carbonate shelf.

In southeastern Arizona, terrigenous clastics of the Earp Formation gradually become higher in section southward towards the Pedregosa Basin (fig. 8). Thus in more northerly sections such as the Gila Mountains, the upper redbed phase consists mostly of the Earp Formation, sections such as Gunnison Hills contain subequal amounts of Earp (clastic) and Horquilla (carbonate), and southerly sections such as Naco Hills are mostly Horquilla. Carbonate-dominated cycles formed on a carbonate shelf (Wilson, 1967), and the following environments are recognized: (1) sublittoral deposits are represented by gray bioturbated lime mudstone with coated algal grains; (2) offshore siliciclastic deposits are represented by fossiliferous, calcareous, ripple-laminated terrigenous mudstone; and (3) storm and (or) tidal-channel deposits are represented by fossiliferous accretal grainstone. Terrigenous-dominated cycles formed at or near shorelines and contain the following environments: (1) fine- to very fine grained quartz sandstone (commonly calcareous hybrid sandstone) formed in barrier-bar complexes; (2) bioturbated calcareous claystone and terrigenous mudstone formed in protected back-bar, nearshore environments; and (3) thin lime-mudstone and bioclastic wackestone formed on the shelf when terrigenous input was reduced or trapped nearshore.

Permian Phases of Deposition

1. *Lower Sandstone Phase (Wolfcampian).* Following withdrawal of the Virgilian sea from much of Arizona, a broad surface of erosion was formed. A drainage system was incised into underlying silty carbonate and limey and dolomitic mudstone and siltstone; lithified material was ripped up and incorporated as clasts in basal Permian deposits. In many places, the lower sandstone phase comprises thin, discontinuous conglomerate, medial redbeds, and upper cross-stratified quartz arenite. Stratigraphic units include the Pakoon, Esplanade, Halgaito, Cedar Mesa, Hermit, Organ Rock, and Earp. Format M of Ross (1973) is included. The triple-basin geometry of the Pennsylvanian was no longer dominant. Rather, the controlling factor of lithofacies distribution was apparently the Sedona Arch (fig. 15). West of the Sedona Arch, widespread, thin, discontinuous conglomerate at the base of the Permian probably formed by fluvial processes (McKee, 1982). Processes associated with probably coastal-plain sedimentation recorded in redbeds and sandstone of the lower Esplanade and equivalent thicker Halgaito are unknown. Cursory examination of several sections suggests that mixed fluvial, tidal, and clastic shoreline deposits are represented in this interval. Marine sandwave, megaripple, and beach deposition (fig. 15) have been documented for parts of the Cedar Mesa and Esplanade by Mack (1979), Lane (1977, 1979), Johansen (1981), and McAllen (1984). Eolian deposition has been documented by Loope (1984) and McAllen (1984). Gypsiferous deposits are reported from the Cedar Mesa (Baars, 1962), Esplanade (McKee, 1982), and Queantoweap (Johansen, 1981). Johansen (1981) suggested a restricted coastal setting for Esplanade and Queantoweap evaporites. In Monument Valley, the Cedar Mesa evaporitic sequence contains cyclic intercalations of cross-stratified sandstone, sandy siltstone, aphanitic dolomite, and gypsum. Eolian, restricted shoreline, and sabkha environments are herein suggested pending further detailed study.

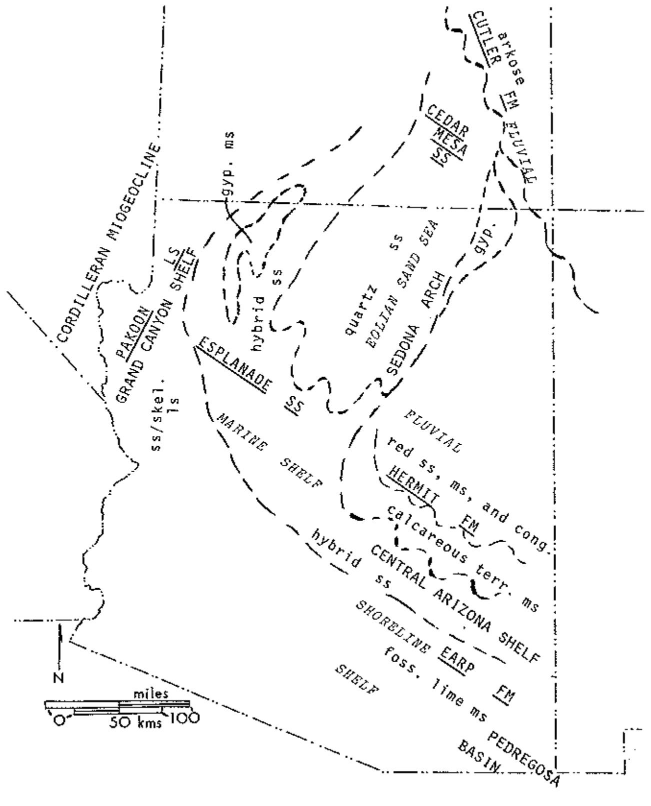


Figure 15. Generalized facies, tectonic elements, and hypothetical paleogeography during maximum extent of quartz arenite of Permian Phase I (Wolfcampian).

East of the Sedona Arch the Cedar Mesa-Esplanade lithofacies are absent and Wolfcampian redbeds are assigned to the Hermit and Organ Rock. This part of the section has received very little study. Abundant plant remains, channel-shaped sandstone and conglomerate, nodular micrite, and structureless to ripple-laminated sandy mudstone suggest deposition on a broad fluvial plain.

In southeastern Arizona, the lower Earp Formation comprises cyclic sandstone, mudstone, and carbonate (Knepp, 1983). The sandstone formed in barrier-bar and higher-energy shoreline environments, the mudstone formed in lower energy protected shoreline environments, and the carbonate formed on offshore carbonate shelves.

2. *Redbed Phase (Wolfcampian-Leonardian).* Without question, this is the least understood phase of deposition. Questions concern its age, correlation, nature of contacts, and depositional systems. The only deposits of this phase that have received modern sedimentological studies are those in the Sedona area (Duffield, 1985) and southeastern Arizona (Ross, 1973; Knepp, 1983). Stratigraphic units include the Hermit, Organ Rock, and Earp Formations (fig. 16). The base of the phase is gradational in many places, although local scoured basal contact with several meters of relief is also widespread (McKee, 1982; Duffield, 1985). The upper contact is sharp to gradational. Format N of Ross (1973), his uppermost format, is represented.

Depositional processes for much of the Hermit have not been documented. White (1929) suggested that the Hermit of Grand Canyon formed on a low-lying, arid, coastal plain (fig. 16). Duffield (1985) documented large-scale point-bar deposits in the Sedona area and suggested that they were part of an avulsing, large meandering river. Smaller scale channel and associated flood-basin deposits were formed by local, arroyo-type systems. Less is known about the

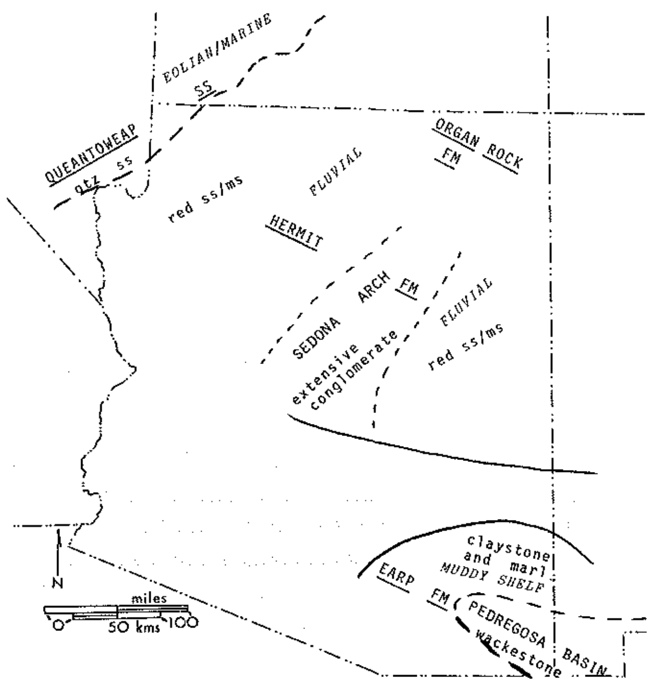


Figure 16. Generalized facies, tectonic elements, and hypothetical paleogeography during Permian Phase II (early Leonardian).

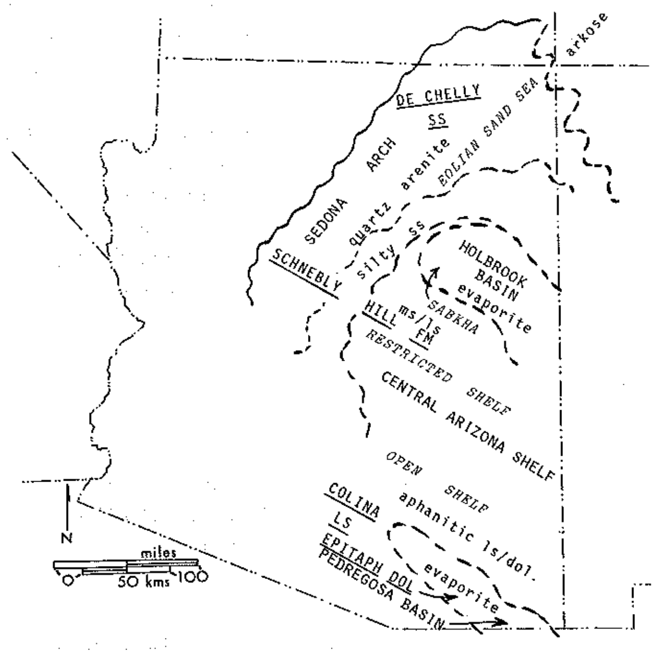


Figure 17. Generalized facies, tectonic elements, and hypothetical paleogeography during deposition of first carbonate tongue above Fort Apache Member of Schnebly Hill Formation during Permian Phase III (middle Leonardian).

depositional system of the Organ Rock, but correlation with and similarity to the Hermit suggest similar depositional history.

In southeastern Arizona, Knepp (1983) has documented deeper water cyclic deposition at the top of the Earp Formation. Claystone and marl and associated fine-grained sandstone formed as basal transgressive deposits of a siliciclastic shoreline-shelf complex. "Mini carbonate cycles" formed in shoaling-upward carbonate shelf environments. Microsparitic wackestone units are tongues of the overlying Colina formed in deeper water.

3. *Sandstone-Redbed-Carbonate Phase (Leonardian).* This phase is only present east of the Sedona Arch. Deposits were laid in and around the Holbrook and Pedregosa basins (fig. 17). The De Chelly Sandstone and Schnebly Hill Formation are associated with the Holbrook Basin, and the Colina Limestone and Epitaph Dolomite are associated with the Pedregosa Basin. A connection between the two areas across the Mogollon shelf is strongly suggested but cannot be proven. Deposits of this phase are cyclic; the cycles are best observed in areas of sharp, lateral facies change. Both lower and upper contacts range from sharp to gradational. West of the Sedona Arch, the phase is represented by the sharp break and presumed unconformity between the Hermit and Coconino.

In the Virgin Mountains, the upper portion of the Queantoweap may contain rocks correlative with this phase. Johansen (1981) reported that much of the upper Queantoweap contains rocks of eolian origin. The Grand Canyon region lacks rocks of this age; however, the broad plain on top of the Hermit Formation was likely a site of regional eolian transport of quartz sand from north to south.

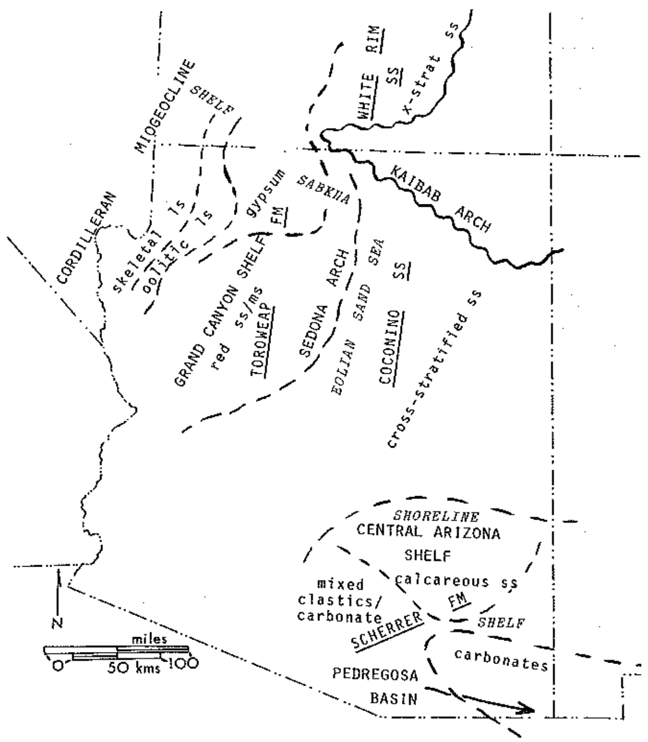


Figure 18. Generalized facies, tectonic elements, and hypothetical paleogeography during deposition of Woods Ranch Member of Toroweap Formation during Permian Phase IV (late Leonardian). Note that this is after maximum extent of Coconino Sandstone.

Sedimentary facies of the Holbrook Basin form a bullseye pattern (fig. 17). The center was the site of fine-grained clastic, carbonate, and evaporite deposition (Peirce and Gerrard, 1966); progressively coarser siliciclastic and quartz arenite deposits rim the basin (fig. 17). Progradation of eolian sands and marine transgression and regression caused complex cyclic intercalation and lateral facies changes. South of Sedona, the lower part of the Schnebly Hill Formation accumulated during rapid marine transgression as a sand wave complex (Blakey, 1984). This was succeeded by a series of rapid marine transgressions and regressive sequences in which restricted marine carbonate, low-energy and rare high-energy shoreline, coastal dune, and inland dune deposits formed (Blakey and Middleton, 1983). Vonderharr (1986) contrasted erg-center and erg-margin dune deposits of the De Chelly Sandstone. Thick evaporite deposits of the basin center formed in restricted marine and continental sabkhas (fig. 17). The Fort Apache Limestone Member formed on a broad, partially restricted carbonate shelf (Gerrard, 1969).

In southeastern Arizona, similar cycles and facies occur in the Colina and Epitaph with the exception of cross-stratified sandstone. In general, the Colina was deposited on a shallow, clear-water, carbonate shelf and the Epitaph formed in restricted environments associated with minor local basins along strike of the Pedregosa Basin (fig. 17). The Colina is fossiliferous limestone at its type section in central Cochise County but fossil content decreases progressively to the northwest in Pima County. Butler (1971) suggested that this indicates a change from subtidal to intertidal. Unabraded shell hash in micritic limestone may have been caused by scavengers that comminuted unwinnowed shell debris on the shallow shelf (Wilt, 1969). The Epitaph Dolomite is a coeval facies of the Colina (fig. 8) developed along the basin axis. Dolomite formed on restricted shoreline carbonate mudflats, and mudstone and gypsum accumulated on sabkha mudflats (fig. 17). The generalized intercalations shown on figure 8 suggest episodic transgression and regression. That the sabkha is coincident with thickest deposition (Butler, 1971) indicates that evaporite-mudflat deposition kept pace with tectonic subsidence. Why more rapidly subsiding portions of the carbonate shelf formed evaporitic mudflats and less rapidly subsiding areas were open-marine shelf is uncertain, but is probably related to local deflection of currents that otherwise would have transported carbonate and terrigenous clastic debris into the evaporitic areas.

4. *Quartz Arenite Phase (Leonardian).* This phase inclues two quartz arenite units, the Coconino Sandstone and Scherrer Formation, and an associated carbonate-evaporite unit, the Toroweap Formation. The name Glorieta Sandstone is used on the eastern Defiance Upwarp along the Arizona-New Mexico border. Where the phase overlies the Hermit and phase 3 is absent, the lower contact is sharp and probably unconformable; where it overlies Schnebly Hill or De Chelly, the contact is a zone of intertonguing. Where the Toroweap is succeeded by the Kaibab, the upper contact was recognized as a regional unconformity by McKee (1938). Where Kaibab directly overlies Coconino, the contact is a zone of reworked quartz sand. In southeastern Arizona both contacts are probably conformable.

In northern Arizona, the Sedona Arch strongly affected facies distribution (fig. 18). The Coconino Sandstone is thin in much of northwestern Arizona but thickens abruptly across and to the east of the structure and reaches maximum thickness of over 330 m in the central Mogollon Rim. Conversely, the Toroweap is thickest in northwestern Arizona and undergoes rapid facies change eastward into Coconino Sandstone (Rawson and Turner-Peterson, 1980) along the Sedona Arch.

West of the Sedona Arch, the following sequences of sedimentation are recognized. Relatively thin (10-20 m) large-scale, high-angle, planar-wedge cross-stratification of the Coconino formed near the western margin of the Coconino eolian sand sea (McKee, 1979). The overlying contorted, locally gypsiferous sandstone of the Seligman Member of the Toroweap Formation formed during initial transgression of the Toroweap sea (Altany, 1979; Rawson and Turner-Peterson, 1980). Local intertonguing of Coconino eolian deposits and Toroweap shoreline and marine deposits was noted by Fisher (1961) in the northwest Grand Canyon. The Brady Canyon Member of the Toroweap formed during maximum development of the Toroweap sea. Several transgressive-regressive cycles were documented by Rawson and Turner-Peterson (1980). Cyclic regression of the Toroweap sea occurred during deposition of the Woods Ranch Member (Altany 1979). Skeletal to peloidal limestone formed on a broad, open carbonate shelf, oolitic grainstone formed in narrow oolitic shoals coincident with the present Hurricane Cliffs, gypsum and thin interbedded aphanitic carbonate formed in coastal sabkhas, and red mudstone and sandstone formed in continental sabkhas (Altany, 1979; Rawson and Turner-Peterson, 1980).

In much of central Arizona, the quartz arenite phase consists solely of the Coconino Sandstone. Eolian sedimentation was continuous in this area while transgressive-regressive cycles were recorded in the Toroweap to the northwest (fig. 18). Sand derived from the north was fed along the western edge of the craton by strong, steady winds and longshore currents (Blakey, 1980). In areas of high subsidence such as the Holbrook Basin, thick accumulations of sand are recorded in the stratigraphic record. Relatively low-energy shoreline zones of the Toroweap sea were incapable of transporting vast amounts of siliciclastic debris so the sand sea was constricted to the east during Toroweap deposition. The change from Toroweap to Coconino deposition is detailed by Rawson and Turner-Peterson (1980).

As the quartz sand blew southward (based on present geography of Arizona) across the state, it encountered a shallow sea in the southeastern portions. The southern Central Arizona Shelf and Pedregosa Basin were the sites of siliciclastic and carbonate-shelf deposition. The Scherrer Formation comprises lower calcareous quartz arenite, middle dolomite and micritic limestone, and upper calcareous quartz arenite (fig. 8). Butler (1971) suggested a high intertidal origin for much of the quartzose deposits. Because modern high intertidal zones are not the sites of clean, well-sorted, quartz arenite sheets, we prefer a general high-energy shoreline-shelf environment until more detailed work is available. The fine-grained carbonate near the middle of the Scherrer is probably a tongue of the overlying Concha Limestone. It is tempting to suggest, though probably difficult to prove, that this tongue is equivalent to the Toroweap of northwestern Arizona.

5. *Upper Carbonate Phase (Leonardian-Guadalupian).* The youngest Permian depositional phase consists chiefly of carbonate rock that at one time may have covered almost the entire state (fig. 19). The Kaibab in the north and Concha and Rainvalley Formations in the southeast are dominantly cherty, fossiliferous, fine-grained dolostone and limestone. They are everywhere truncated by a major unconformity and are overlain by rocks and sediments ranging from Triassic to Recent in age.

The Kaibab Formation has been extensively studied; however, a complicated diagenetic history has erased many depositional details. The Fossil Mountain Member accumulated on a broad carbonate shelf during several marine transgressions and regressions. Both open-marine (skeletal limestone and dolomite) and restricted-marine (dolomitic mudstone and sandstone and sandy dolomite) conditions were present (Cheevers and Rawson, 1979). The former generally lay to the west and the latter to the east of the present axis of the Kaibab Upwarp. Thus, like most other units in this study, the Kaibab underwent significant change across the Paleozoic Sedona Arch. Unlike many of the other Pennsylvanian and Permian carbonate units, the change from open to restricted shelf is unmarked by shoals, as grainstone is generally absent from the Kaibab (Cheevers and Rawson, 1979). The shore of the Kaibab sea was a broad sandy to dolomitic mud flat (fig. 19). Possible intertonguing of the Kaibab with the upper Coconino may suggest local eolian deposition in the Holbrook area. Overlying redbeds, gypsum, and dolomitic mudstone of the Harrisburg Member formed during cyclic regression of the Kaibab sea (Cheevers and Rawson, 1979).

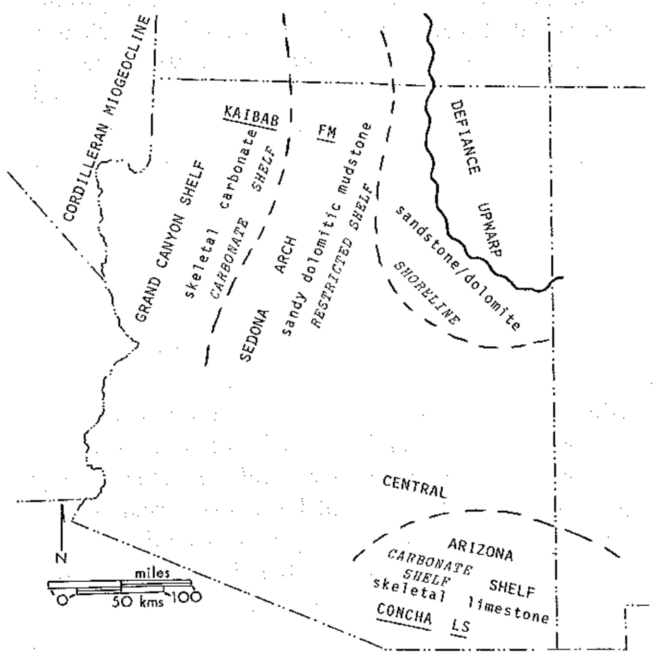


Figure 19. Generalized facies, tectonic elements, and hypothetical paleogeography during maximum transgression of Fossil Mountain Member of Kaibab Formation during Permian Phase V (Latest Leonardian-Guadalupian).

Similar deposition occurred in southeastern Arizona during formation of the Concha and Rainvalley formations. The cherty fossiliferous limestone of the Concha was deposited on a broad, shallow, quiet-water, carbonate shelf (Butler, 1971). The thin-bedded limestone and interbedded dolostone of the overlying Rainvalley have been interpreted as a shoaling and shallowing of the Permian sea in southwestern Arizona (Butler, 1971). A recent study reported that environments ranged from subtidal to lower supratidal in the Rainvalley with spatial distribution of facies suggesting the presence of a paleoshoreline in the Waterman Mountains (Vaag, 1984, p. 86).

Following withdrawal of Permian seas, the state was subjected to a long period of weathering and erosion. Following a prolonged hiatus, northern Arizona continued to accumulate continental and shallow-marine deposits across broad areas in relatively stable tectonic settings (Blakey, this volume; Nations, this volume). However, southern Arizona became tectonically unstable, with scattered areas of uplift and erosion coupled with local basins that received thick clastic and carbonate deposits.

CONCLUSIONS

Discussion and Suggestions for Future Work

The presentation of the geologic history of the Pennsylvanian and Permian of Arizona would not be possible without accurate regional correlation of the stratigraphic units. Correlations presented herein are based on (1) fossil evidence; (2) event stratigraphy: correlation of major pulses of sedimentation based on detailed description of local sections; (3) correlation of local marker beds; and (4) as a last resort, intuitive "best fit" within the constraints of known regional stratigraphy and hypothetical paleogeography. This last method was used mainly in long-range correlations from northern to southern Arizona.

Not all Pennsylvanian and Permian rocks in the state are well known. Sequences lacking modern stratigraphic and sedimentologic studies include the following: (1) carbonate sequences of the Virgin Mountains; (2) most evaporite units, especially those of phases 1-3 of the Permian; (3) many fine-grained redbeds, especially the Halgaito, Organ Rock, and Hermit; (4) most of the Permian rocks of southeastern Arizona; (5) the Pennsylvanian rocks of northeastern Arizona; and (6) the Kaibab Formation of the Mogollon Rim. Other suggested topics of further study include: (1) detailed paleontologic, especially microfossil analysis of the Supai Group of the Mogollon Rim; (2) detailed stratification study of the Coconino Sandstone and Scherrer Formation; (3) detailed study of eolian deposits of Esplanade and Cedar Mesa Sandstones; (4) detailed study of Late Pennsylvanian siliciclastic units of Earp and Horquilla Formations, Mogollon Rim; and (5) detailed study of carbonate-siliciclastic facies changes, western Grand Canyon and Virgin Mountains.

Summary of Geologic History

1. Pennsylvanian deposition was initiated by incursion of the sea in extreme northwestern, northeastern, and southeastern Arizona. Conglomerate, fine-grained siliciclastic, and aphanitic limestone units document a progression toward clear-water carbonate shelf deposition.

2. Following a brief early Atokan hiatus, cyclic clastic and carbonate shelf deposition occurred in the three above-mentioned depositional sites.

3. Cyclic Desmoinesian and Missourian carbonate and thin siliciclastic deposits formed east of the Sedona Arch. The cycles were deposited during repeated transgressive-regressive cycles.

4. During the Virgilian, most of Arizona was the site of siliciclastic and carbonate cyclic marine and coastal-plain deposition. Carbonate percentage increased towards the three depositional centers.

5. Following a period of erosion in most places, siliciclastic marine, coastal-plain, and local eolian deposition were initiated during the early Permian. Quartz arenite dominates Wolfcampian rocks west of the Sedona Arch.

6. Latest Wolfcampian and early Leonardian rocks are dominantly red, fine-grained siliciclastics. Fluvial and coastal-plain sedimentation were dominant across the northern two-thirds of the state; marine and shoreline deposition took place to the southeast.

7. Middle Leonardian deposition was restricted to the eastern part of the state. Siliciclastic sedimentation dominated to the north; carbonate percentage increased southward. Cyclic eolian, sabkha, coastal-plain, shoreline, and shallow-marine deposits were associated with rapid subsidence in the Holbrook and Pedregosa Basins.

8. Late Leonardian sedimentation was dominated by extensive quartz arenite formation. Eolian environments prevailed with cyclic sabkha, shoreline, and shallow-marine deposits present in northwestern and southeastern Arizona.

9. The last Paleozoic sedimentary event was the formation of widespread dolomitic limestone and sandy dolomite during a late Leonardian to early Guadalupian marine event. The sea gradually withdrew from the state and a long period of erosion followed.

ACKNOWLEDGMENTS

Some of Blakey's field work was supported by grants from the Organized Research Committee, Northern Arizona University. The manuscript was reviewed by Wes Peirce, Arizona Geological Survey, Tucson, and Bill Butler, U.S. Geological Survey, Denver, and benefited greatly from their comments. Much of the drafting was by Teresa Meuller; Louella Holter typed the manuscript.

REFERENCES

Altany, R. M., 1979, Facies of the Hurricane Cliffs tongue of the Toroweap Formation, northwestern Arizona, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 101-104.

Baars, D. L., 1962, Permian system of Colorado Plateau: American Association of Petroleum Geologists Bulletin, v. 46, p. 149-218.

Baars, D. L., 1979, The Permian System, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 1-6.

Baars, D. L., Parker, J. W., and Chronic, J., 1967, Revised stratigraphic nomenclature of Pennsylvanian System, Paradox Basin: American Association Petroleum Geologists Bulletin, v. 51, p. 393-403.

Baker, A. A., and Reeside, J. B., 1929, Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 13, p. 1413-1448.

Bissell, H. J., 1969, Permian and Lower Triassic transition from the shelf to basin (Grand Canyon, Arizona to Spring Mountains, Nevada), *in* Baars, D. L., ed., Geology and natural history of the Grand Canyon region: Durango, Colorado, Four Corners Geological Society, 5th Field Conference Guidebook, p. 135-169.

Blakey, R. C., 1979a, Stratigraphy of the Supai Group (Pennsylvanian-Permian), Mogollon Rim, Arizona, *in* Beus, S. S., and Rawson, R. R., eds., Carboniferous stratigraphy in the Grand Canyon country, northern Arizona and southern Nevada: Field trip no. 13, Ninth International Congress of Carboniferous Stratigraphy and Geology: American Geological Institute, p. 89-104.

Blakey, R. C., 1979b, Lower Permian stratigraphy of the southern Colorado Plateau, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 115-129.

Blakey, R. C., 1979c, Oil-impregnated carbonate rocks of the Timpoweap Member, Moenkopi Formation, Hurricane Cliffs area, Utah and Arizona: Utah Geology, v. 6, p. 45-54.

Blakey, R. C., 1980, Pennsylvanian and Early Permian paleogeography, southern Colorado Plateau and vicinity, *in* Fouch, T. D., and Magathan, E. R., eds., Paleozoic paleogeography of the west-Central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 239-257.

Blakey, R. C., 1984, Marine sand-wave complex in the Permian of central Arizona: Journal of Sedimentary Petrology, v. 54, p. 29-51.

Blakey, R. C., and Middleton, L. T., 1983, Permian shoreline eolian complex in central Arizona: dune changes in response to cyclic sea level changes, *in* Brookfield, M. E., and Ahlbrandt, T. S., eds., Eolian sediments and processes: Amsterdam, Elsevier, Developments in Sedimentology, no. 38, p. 551-581.

Brew, D. C., 1965, The Naco Formation (Pennsylvanian) in central Arizona: Ithaca, New York, Cornell University, unpublished Ph.D. dissertation, 201 p.

Brown, J. W., 1969, Stratigraphy and petrology of the Kaibab Formation between Desert View and Cameron, northern Arizona, *in* Baars, D. L., ed., Geology and natural history of the Grand Canyon region: Durango, Colorado, Four Corners Geological Society, 5th Field Conference Guidebook, p. 170-173.

Bryant, D. L., 1959, Marker zones in Permian formations of southern Arizona, *in* Heindl, L. A., ed., Southern Arizona guidebook II: Tucson, Arizona Geological Society, p. 38-42.

Bryant, D. L., 1968, Diagnostic characteristics of the Paleozoic formations of southeastern Arizona, *in* Titley, S. R., ed., Southern Arizona guidebook III: Tucson, Arizona Geological Society, p. 33-47.

Bryant, D. L., and McClymonds, N. E., 1961, Permian Concha Limestone and Rainvalley Formation, southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 45, p. 1324-1333.

Butler, W. C., 1971, Permian sedimentary environments in southeastern Arizona, *in* McCullough, E. J., ed.: Tucson, Arizona Geological Society Digest, v. 9, p. 71-94.

Canwright, J. E., 1978, Palynomorph assemblages from the Supai Formation of Arizona as indicators of age [abs.]: Geological Society of America, Cordilleran Section, Tempe, Arizona, Abstracts with Programs, v. 10, p. 98.

Cheevers, C. W., and Rawson, R. R., 1979, Facies analysis of the Kaibab Formation in northern Arizona, southern Utah, and southern Nevada, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 105-113.

Cooper, J. R., 1959, Reconnaissance geologic map of southeastern Cochise County, Arizona: U.S. Geological Survey Mineral Investigations Field Study Map MF-213, scale 1:125,000.

Darton, N. H., 1910, A reconnaissance of parts of northwestern Arizona: U.S. Geological Survey Bulletin 435, 88 p.

Dockter, R. D., and Keith, W. J., 1978, Reconnaissance geologic map of Vekol Mountains quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-931, scale 1:62,500.

Drewes, Harald, 1981, Geologic map and sections of the Bowie Mountain South quadrangle, Cochise County, Arizona: U.S. Geological Survey Miscellaneous Investigations Map I-1363, scale 1:24,000.

Drewes, Harald, 1982, Geologic map of the Cochise Head quadrangle and adjacent areas, southeastern Arizona: U.S. Geological Survey Miscellaneous Investigations Map I-1312, scale 1:24,000, 2 sheets.

Duffield, J. A., 1985, Depositional environments of the Hermit Formation of central Arizona: Flagstaff, Northern Arizona University, unpublished M. S. thesis, 82 p.

Elston, D. P., and DiPaolo, W. D., 1979, Pennsylvanian-Permian stratigraphy of the Sedona area and environs, central and northern Arizona, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 131-141.

Fisher, W. L., 1961, Upper Paleozoic and lower Mesozoic stratigraphy of Parashant and Andrus Canyons, Mohave County, northwestern Arizona: Lawrence, University of Kansas, unpublished Ph. D. thesis, 345 p.

Gallaher, D. W., 1984, Stratigraphic geostatistical analysis of the Supai Group of northern Arizona, Flagstaff, Northern Arizona University, unpublished M. S. thesis, 87 p.

Gerrard, T. A., 1969, Stratigraphy of the Fort Apache Member Supai Formation (Permian), east-central Arizona, *in* Baars, D. L., ed., Geology and natural history of the Grand Canyon region: Durango, Colorado, Four Corners Geological Society, 5th Field Conference Guidebook, p. 174-180.

Gilluly, James, Cooper, J. R., and Williams, J. S., 1954, Late Paleozoic stratigraphy of central Cochise County, Arizona: U.S. Geological Survey Professional Paper 266, 49 p.

Gregory, H. E., 1917, Geology of the Navajo country: a reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 93, 161 p.

Huddle, J. W., and Dobrovolny, E., 1945, Late Paleozoic stratigraphy of central and northeastern Arizona: U.S. Geological Survey Oil and Gas Investigations, Preliminary Chart 10.

Irwin, J. H., Stevens, P. R., and Cooley, M. E., 1971, Geology of the Paleozoic rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 521-C, 32 p.

Johansen, S. J., 1981, Depositional environments of the Queantoweap Sandstone of northwestern Arizona and southern Arizona: Tucson, University of Arizona, unpublished M. S. thesis, 213 p.

Knepp, Rex, 1983, Depositional framework of lower Naco Group strata (Pennsylvanian-Permian), northern shelf of the Pedregosa Basin, Arizona: Tucson, University of Arizona, pre-publication manuscript, 76 p.

Krieger, M. H., 1965, Geology of the Prescott and Paulden quadrangles, Arizona: U.S. Geological Survey Professional Paper 467, 127 p.

Lane, C. L., 1977, Pennsylvanian-Permian stratigraphy of west-central Arizona: Flagstaff, Northern Arizona University, unpublished M. S. thesis, 120 p.

Lane, C. L., 1979, Regional correlation of the Esplanade Sandstone, west-central Arizona, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 81-85.

Langenheim, R. L., and Webster, G. D., 1979, Stop descriptions—sixth day, *in* Beus, S. S., and Rawson, R. R., eds., Carboniferous stratigraphy in the Grand Canyon country, northern Arizona and southern Nevada: Field trip no. 13, 9th International Congress of Carboniferous Stratigraphy and Geology: American Geological Institute, p. 53-60.

Lehner, R. E., 1958, Geology of the Clarkdale quadrangle, Arizona: U.S. Geological Survey Bulletin 1021-N, p. 511-592.

Loope, D., 1984, Eolian origin of upper Paleozoic sandstones, southeastern Utah: Journal of Sedimentary Petrology, v. 54, p. 563-580.

Luepke, Gretchen, 1971, A re-examination of the type section of the Scherrer Formation (Permian) in Cochise County, Arizona, *in* McCullough, E. J., ed.: Tucson, Arizona Geological Society Digest, v. 9, p. 245-257.

Mack, G. H., 1979, Littoral marine depositional model for the Cedar Mesa Sandstone (Permian), Canyonlands National Park, Utah, *in* Baars, D. L., ed., Permianland: Durango, Colorado, Four Corners Geological Society, 9th Field Conference Guidebook, p. 33-37.

McAllen, W. R., 1984, Petrology and diagenesis of the Esplanade Sandstone, central Arizona: Flagstaff, Northern Arizona University, unpublished M. S. thesis, 90 p.

McClymonds, N. E., 1959, Paleozoic stratigraphy of the Waterman Mountains, Pima County, Arizona, *in* Heindl, L. A., ed., Southern Arizona guidebook II: Tucson, Arizona Geological Society, p. 66-76.

McKee, E. D., 1938, The environment and history of the Toroweap and Kaibab formations of northern Arizona and southern Utah: Carnegie Institution of Washington, Publication 492, 268 p.

McKee, E. D., 1945, Oak Creek Canyon: Plateau, v. 18, p. 25-32.

McKee, E. D., 1975, The Supai Group, subdivision and nomenclature: U.S. Geological Survey Bulletin 1395-J, 11 p.

McKee, E. D., 1979, Ancient sandstones considered to be eolian, *in* McKee, E. D., ed., A study of global sand seas: U.S. Geological Survey Professional Paper 1052, p. 187-238.

McKee, E. D., 1982, The Supai Group of Grand Canyon: U.S. Geological Survey Professional Paper 1173, 504 p.

McKee, E. D., and Pierce, W., 1982, Petrography of the Supai Group and Pakoon Limestone, *in* McKee, E. D., The Supai Group of Grand Canyon: U.S. Geological Survey Professional Paper 1173, p. 333-359.

McNair, A. H., 1951, Paleozoic stratigraphy of part of northwestern Arizona: American Association of Petroleum Geologists Bulletin, v. 35, p. 503-541.

Merrill, W. M., and Winar, R. M., 1958, Molas and associated formations in San Juan Basin-Needle Mountains area, southwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 42, p. 2107-2132.

Miller, F. K., and McKee, E. H., 1971, Thrust and strike-slip faulting in the Plomosa Mountains, southwestern Arizona: Geological Society of America Bulletin, v. 82, p. 717-722.

Nations, J. D., 1963, Evidence for a Morrowan age for Black Prince Limestone of southeastern Arizona: Journal of Paleontology, v. 37, p. 1252-1264.

Nielson, R. L., and Johnson, J. L., 1979, The Timpoweap Member of the Moenkopi Formation, Timpoweap Canyon, Utah: Utah Geology, v. 6, p. 17-28.

Noble, L. F., 1922, A section of Paleozoic formations of the Grand Canyon at Bass Trail: U.S. Geological Survey Professional Paper 131, p. 23-73.

Patch, S., 1969, Petrology and stratigraphy of the Epitaph Dolomite (Permian) in the Tombstone Hills, Cochise County, Arizona: Tucson, University of Arizona, unpublished M. S. thesis, 42 p.

Peirce, H. W., 1964, Internal correlation of the Permian De Chelly Sandstone, Defiance Plateau, Arizona: Contributions to the Geology of Northern Arizona, Museum of Northern Arizona Bulletin, v. 40, p. 15-31.

Peirce, H.W., 1967, Permian stratigraphy of the Defiance Plateau, Arizona, *in* Trauger, F. D., ed., Defiance-Zuni-Mt. Taylor region: Socorro, New Mexico Geological Society, 18th Field Conference Guidebook, p. 57-62.

Peirce, H. W., and Gerrard, T. A., 1966, Evaporite deposits of the Permian Holbrook Basin, Arizona: Northern Ohio Geological Society Second Symposium on Salt, v. 1, p. 1-10.

Peirce, H. W., Jones, N., and Rogers, R., 1977, A survey of uranium favorability of Paleozoic rocks in the Mogollon Rim and Slope region, east-central Arizona: Tucson, Arizona Bureau of Geological and Mineral Technology Circular 19, 60 p.

Pope, R. W., 1976, An analysis of the carbonate facies of the Hermosa Formation (Pennsylvanian) of northeastern Arizona: Flagstaff, Northern Arizona University, unpublished M. S. thesis, 134 p.

Rawson, R. R., and Turner-Peterson, C. W., 1980, Paleogeography of northern Arizona during the deposition of the Permian Toroweap Formation, *in* Fouch, T. D., and Magathan, E. R., eds., Paleozoic paleogeography of the west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 341-352.

Rea, D. K., and Bryant, D. L., 1968, Permian red chert-pebble conglomerate in Earp Formation, southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 52, p. 809-819.

Read, C. B., and Wanek, A. A., 1961, Stratigraphy of outcropping Permian rocks in parts of northeastern Arizona and adjacent areas: U.S. Geological Survey Professional Paper 374-H, p. H1-H10.

Ross, C. A., 1973, Pennsylvanian and Early Permian depositional history, southeastern Arizona: American Association of Petroleum Geologists Bulletin, v. 57, p. 887-912.

Sabins, F. F., Jr., and Ross, C. A., 1965, Stratigraphy and fusulinids of Naco Group in Chiricahua and Dos Cabezas mountains, Arizona, *in* Fitzsimmons, P. J., and Lochman-Balk, C., eds., Southwestern New Mexico II: New Mexico Geological Society Guidebook, 16th Annual Field Conference, p. 148-157.

Sorauf, J. E., 1962, Structural geology and stratigraphy of the Whitmore area, Mohave County, Arizona: Lawrence, University of Kansas, unpublished Ph. D. thesis, 361 p.

Steed, D. A., 1980, Geology of the Virgin River Gorge, northwest Arizona: Provo, Brigham Young University Geological Studies, v. 27, part. 3, p. 96-114.

Thompson III, Sam, and Jacka, A. D., 1981, Pennsylvanian stratigraphy, petrography, and petroleum geology of Big Hatchet Peak section, Hidalgo County, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Circular 176, 125 p.

Titley, S. R., 1976, Evidence for a Mesozoic linear tectonic pattern in southeastern Arizona, *in* Wilt, J. C., and Jenney, J. P., eds., Tectonic digest: Tucson, Arizona Geological Society Digest, v. 10, p. 71-101.

Vaag, M. K., 1984, Stratigraphy of Permian Rainvalley Formation, southeastern Arizona: Tucson, University of Arizona, unpublished M. S. thesis, 135 p.

Vonderharr, J., 1986, Sedimentology and paleoecology of the De Chelly Sandstone (Permian) of northeastern Arizona: Flagstaff, Northern Arizona University, unpublished M. S. thesis, 137 p.

Welch, J. E., 1959, Biostratigraphy of the Pennsylvanian and Permian Systems in southern Nevada: Salt Lake City, University of Utah, unpublished Ph. D. thesis, 215 p.

Weisman, M. K., 1986, Geology of the Pine and northern Buckhead Mesa quadrangles, central Arizona: Flagstaff, Northern Arizona University, unpublished M. S. thesis, 126 p.

Wengerd, S. A., 1962, Regional structural-stratigraphic cross section, east-central Arizona to west-central New Mexico, *in* Weber, R. H., and Peirce, H. W., eds., Mogollon Rim region, east-central Arizona: Socorro, New Mexico Geological Society, 13th Field Conference Guidebook, p. 58.

Wengerd, S. A., and Matheny, M. L., 1958, Pennsylvanian System of Four Corners region: American Association of Petroleum Geologists Bulletin, v. 42, p. 2048-2106.

White, D., 1929, Flora of the Hermit Shale, Grand Canyon, Arizona: Carnegie Institution of Washington Publication 405, p. 1-221.

Wilson, J. L., 1967, Cyclic and reciprocal sedimentation in Virgilian strata of southern New Mexico: Geological Society of America Bulletin, v. 78, p. 805-818.

Wilt, J. C., 1969, Petrology and stratigraphy of the Colina Limestone (Permian) in Cochise County, Arizona: Tucson, University of Arizona, unpublished M. S. thesis, 117 p.

Winters, S. S., 1963, Supai Formation (Permian) of eastern Arizona: Geological Society of America Memoir 89, 99 p.

Zeller, R. A., 1965, Stratigraphy of the Big Hatchet Mountains area, New Mexico: Socorro, New Mexico Bureau of Mines and Mineral Resources Memoir 16, 128 p.

Revised manuscript accepted 1986.