CHERTIFICATION OF THE REDWALL LIMESTONE
(MISSISSIPPIAN), GRAND CANYON
NATIONAL PARK, ARIZONA

by
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July 25, 1985
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ABSTRACT

Microfabrics of various chert types in the Redwall Limestone of the Grand Canyon show that, despite obvious macroscopic differences, all share a common diagenetic history. In the field, six stratigraphically-controlled types of chert were recognized based on geometry, size, internal structure, and color. Petrographically, all have a consistent paragenesis: 1) microcrystalline quartz (lime mud and allochem replacement), 2) length-fast chalcedony (void-filling cement), and 3) megaquartz (allochem replacement and post-chalcedony void-filling cement). This paragenetic sequence and published stable isotope data both support the mixing zone model of chertification proposed by Knauth. Siliceous sponge spicules in cherts suggest an indigenous silica source; the diagenetic sequence may reflect progressively diminished supply of biogenic silica and resultant dilution of pore waters. Evidence of incipient dolomitization preserved within cherts is obscured in host carbonate by later wholesale dolomitization.
INTRODUCTION

Nodular and bedded cherts have been the subject of numerous investigations from both field and petrographic approaches (Choquette, 1955; Biggs, 1957; Wilson, 1966; McBride, 1979); however, few studies have concentrated on the basic questions of timing, silica source, and diagenetic environment of chertification. One exception is research by Meyers (1977) which documents facies selectivity of chert in the Lake Valley Formation of New Mexico.

The Redwall Limestone offers an excellent opportunity to study chert in a shallow water carbonate sequence. The Redwall contains a variety of chert types ranging from oblate nodules to laterally persistent, irregular pseudobeds. These chert types are distributed with varying abundance in the Redwall.

Although chert is present in all four members of the Redwall, it is especially abundant in the Thunder Springs Member, described by McKee (1960b, p. B461) as "thin beds of white chert and gray carbonate rock in an alternating sequence". McKee (1960b) characterized the morphology and variable abundance of cherts in the Thunder Springs; however, a comparable study of cherts in the other three members was previously lacking. In addition, cherts throughout the Redwall still required detailed petrographic analysis to determine the role of various diagenetic controls on chertification.
The objectives of this study are: 1) recognize natural classes of cherts based on field description and laboratory analysis and establish their facies distribution; 2) infer timing of chertification from diagenetic histories of cherts and their host carbonate rocks; 3) determine source(s) of silica; and 4) construct a model for chertification which describes the diagenetic environment in which Redwall chert, and other similar cherts, may have formed.

Location of Study Area

The spectacular cliffs of the Redwall Limestone in the Grand Canyon have been the subject of scenic and scientific interest ever since their exposures were first recognized in 1858 by J.S. Newberry (McKee and Gutschick, 1969, p. 5). Only within the Grand Canyon is the Redwall so well-exposed and complete, attaining a stratigraphic thickness of 150 to 215 m (500 to 700 ft) and including all four members. The quality of exposure in these cliffs permits accurate determination of the geometry and scale of chert bodies, some of which extend great distances. Furthermore, trails maintained in the Grand Canyon National Park provide access to the Redwall cliffs.

The study area concentrates on exposures of the Redwall Limestone along the South Kaibab Trail (Figs. 1, 2). Two subparallel faults in the Redwall cross the South Kaibab Trail, leaving a down-dropped central block. The Whitmore Wash Member was measured on the north fault block, the Thunder Springs Member on the central block, and the Mooney Falls and Horseshoe Mesa Member on the south block.
Fig. 1. Map of Grand Canyon National Park showing location of study area.
Fig. 2. Redwall Limestone along South Kaibab Trail.
**Methods of Investigation**

The complete stratigraphic section (Appendix) of Redwall Limestone was measured in detail using a metric Jacob staff and a Brunton compass. Bedding dips were checked periodically, but the essentially flat-lying beds required no corrections for dip. Samples for laboratory analysis were collected as the section was measured and described.

The bulk of the laboratory analyses consists of petrographic examination of 70 thin sections. Thin sections of chert containing carbonate host rock or included carbonate were stained with Alizarin Red-S to distinguish calcite from dolomite (Friedman, 1959).

Additional laboratory work included X-ray diffractometry (XRD), scanning electron microscopy (SEM), and energy dispersive X-ray analysis (EDXA). XRD samples were ground to a fine powder and mounted on glass slides using standard acetone or isopropyl alcohol slurry techniques. Mineral phases present on X-ray diffractograms were identified by computer (MICRO-ID: Minerals Software) and verified manually. SEM samples were coated with a mixture of Au and Pd before examination under the SEM microscope and analysis by the attached EDXA unit.

**Previous Work**

The Redwall Limestone was named by Gilbert in 1875 for the red appearance of its escarpments on either side of the Grand Canyon (Gilbert, 1875, p. 177). Originally called both the 'Red Wall limestone' (p. 177) and the 'Red Wall group' (Fig. 81) by Gilbert, it
included strata of Devonian, Mississippian, Pennsylvanian, and possibly Permian age (Peirce, 1979, p. 23) and had an average thickness of 760 m (2500 ft).

Originally, the 'Redwall group' was composed of three units: dense limestone with shaley bands, overlain by a 244 to 305 m (800 to 1000 ft) sheer perpendicular limestone cliff, in turn overlain by 60 to 150 m (200 to 500 ft) of alternating sandstone and limestone (Gilbert, 1875, p. 178). In a stratigraphic column drawn by Gilbert (in Marvine, 1875, Fig. 82), the 245 m (800 ft) thick massive limestone with sheer escarpment is called the 'Red-wall limestone'. This unit corresponds essentially to the Redwall Limestone of current usage (Fig. 3).

Walcott (1880, p. 222) labeled 295 m (970 ft) of arenaceous cherty limestone and massive limestone as the 'Red Wall Limestone'. He was the first to recognize the pre-Redwall unconformity, describing the contact between Devonian sandstones and impure limestones and the Carboniferous Red Wall Limestone as a "plane of unconformity by erosion" (Walcott, 1880, p. 222).

The Redwall Limestone was later restricted to include only 170 to 245 m (550 to 800 ft) of massive light gray limestone (Darton, 1910, p. 21-22). Darton removed the lower member of Gilbert's (1875) stratigraphic section, and suggested that the upper member more properly belonged in the Supai. Darton designated a type locality for the newly defined Redwall Limestone in the Shinumo drainage basin on the north side of the Grand Canyon, and named the type locality Redwall Canyon so
Fig. 3. Historical development of Redwall Limestone nomenclature. (After McKee and Gutschick, 1969).
that 'Redwall' would meet the requirements for the name of a lithostratigraphic unit (Darton, 1910, p. 22).

Walcott (in Noble, 1922, Pl. XIX) was the first worker to subdivide the Redwall Limestone, although his definition included Pennsylvanian strata. Unit D, at the base of the Redwall, is described as 26 m (85 ft) of light gray limestones. Unit C is composed of 44 m (145 ft) of light gray limestone with chert in layers or nodules. Unit B contains 145 m (477 ft) of massive light gray limestone. Unit A, at the top of Walcott's Redwall, is 70 m (225 ft) of sandstone and limestone containing Pennsylvanian age fossils at some localities. Units D and C correspond to the basal two members of current subdivision, and Unit B approximates the upper two members.

Noble (1922, p. 54) redefined the Redwall Limestone, excluding the 155 m (510 ft) of Pennsylvanian strata which Barton (1910) had previously assigned to the Supai. His definition of the formation formally restricted the Redwall to massive gray limestones of Mississippian age.

The first detailed stratigraphic section was measured by Noble (1922) at the Bass Trail in the Grand Canyon. Noble (1922, p. 54, Pl. XIX) subdivided the Redwall into three units based on topographic expression. His Subdivision C, at the base of the formation, is a 2.4 m (8 ft) thick unit of slope-forming sandy breccia. Subdivision B, 152 m (500 ft) thick, is a massive limestone cliff. Subdivision A, at the top of the formation, is a 20 m (62 ft) thick unit of distinctly bedded limestone which forms a series of small cliffs and narrow ledges. In addition, Noble (1922, p. 58) recognized a "probable
unconformity between Mississippian and Pennsylvanian strata" in exposures along Hermit, Bright Angel, and Hance Trails.

Gutschick (1943) studied the Redwall Limestone in Yavapai County, Arizona. The four members (in ascending order: I, II, III, IV) he informally recognized and described (p. 2-5) are the same ones currently in use. The members were found regionally traceable by Easton and Gutschick (1953).

McKee (1963) formally named these four members of the Redwall. In ascending order, they are Whitmore Wash Member, Thunder Springs Member, Mooney Falls Member, and Horseshoe Mesa Member. The names were taken from geographic localities where the rocks are well-exposed and appropriate type sections had been measured in detail.

Purves (1978, p. 35) compiled a list of major contributions to Redwall stratigraphy, areal extent, and nomenclatural development. Significant publications on the Redwall in the Grand Canyon not previously mentioned have been authored by Ransome (1916), Zeller (1957), McKee (1960a,c); west of the Grand Canyon area by McNair (1951); south of the Grand Canyon area by Woodell (1927), Stoyanow (1936), J. Smith (1974), and Racey (1974); in central Arizona by Huddle and Dobrovolny (1945, 1952), and Racey (1974); and in the subsurface of northern and northeastern Arizona by McKee (1958), Elston (1960), Parker and Roberts (1966), Peirce, Keith, and Wilt (1970), Peirce and Scurlock (1972), and Kent (1975).

Comprehensive faunal lists and discussions of Redwall systematic paleontology are available in McKee and Gutschick (1969). This volume includes chapters on foraminifera, corals, bryozoans,
brachiopods, gastropods and pelecypods, cephalopods, blastoids, crinoids, and miscellaneous fossil groups.

Other paleontological publications include foraminiferal biostratigraphic studies by Zeller (1957), Skipp (1963), Skipp, Halcomb, and Gutschick (1966), and Mamet and Skipp (1970); conodont biostratigraphic work by Racey (1974); studies on Redwall corals by Easton and Gutschick (1953) and Sando (1963, 1964); cephalopod studies by Miller, Downs, and Youngquist (1949); and a discussion on crinoids by Stoyanow (1936). Spamer (1983) has compiled an annotated bibliography, 1857-1982, of geology of the Grand Canyon, with an annotated catalog of Grand Canyon type fossils.
The four subdivisions (Fig. 3) of the Redwall Limestone recognized by Gutschick (1943) were designated formal members by McKee (1963). This fourfold division has been widely accepted by subsequent workers and is now in general use. From base to top these units are Whitmore Wash Member, Thunder Springs Member, Mooney Falls Member, and Horseshoe Mesa Member. Each member is described in detail in this chapter and in the Appendix.

**Thickness**

The Redwall Limestone (Fig. 2) forms a spectacular massive cliff in the walls of the Grand Canyon. At the eastern end of the Grand Canyon the Redwall is less than 152 m (500 ft) thick, and at the western end it thickens to more than 213 m (700 ft) (McKee and Gutschick, 1969, p. 1). At the type locality, Redwall Canyon in the central Grand Canyon, Darton (1910, p. 21) indicated a thickness of "about 800 feet" (244 m) of Redwall Limestone. However, Darton's estimate most likely included beds later transferred to the Supai by Noble (1922).

Since the Bass Trail section is only four miles south of Redwall Canyon, Noble (1922, p. 57) concluded that his measured section (174 m; 570 ft) at Bass Canyon would "represent the formation at the type locality." For the Bass Trail section, McKee and Gutschick, 1969, p. 625-626) reported a total Redwall thickness of 182 m (597.5 ft).
Isopach data (McKee and Gutschick, 1969, Fig. 2; McKee, 1979, Pl. 7; Peirce, 1979, Fig. 2; and others; Fig. 4) show that the Redwall thins to the south in Chino Valley and along the Mogollon Rim, and to the east in the subsurface. The Redwall thins to zero isopach around the Defiance-Zuni positive element on the northern part of the Arizona-New Mexico state boundary. A maximum thickness of more than 244 m (800 ft) occurs in extreme northwestern Arizona near Lake Mead (McKee, 1979, p. 205).

Distribution

The name Redwall has been applied to all Mississippian limestones of northern Arizona and most of central Arizona. In east-central Arizona the Modoc Limestone was named by Lindgren (1905a,b). Mississippian limestones of southern and southeastern Arizona are called Escabrosa Limestone (Ransome, 1904). North of Arizona, Mississippian limestones extending into southwestern Colorado are named Leadville, and into eastern Utah and Wyoming are called Madison Limestone. No sharp boundaries are recognized between the Redwall and adjacent formations because the Redwall almost certainly was originally part of a larger rock body which was continuous with these other units (McKee and Gutschick, 1969, p. 4; Gutschick and Sandberg, 1983, p. 89).

Basal Contact of the Redwall Limestone

The Redwall Limestone unconformably overlies the Upper Devonian Temple Butte Formation in most of the Grand Canyon, but overlies the Middle Cambrian Muav Limestone in some parts of the eastern Grand
Fig. 4. Total isopach map of northern Arizona. (From McKee and Gutschick, 1969).
Canyon (Stoyanow, 1948, p. 314; McKee and Gutschick, 1969, Fig. 4, Table 2). In the subsurface of northeastern Arizona the Redwall overlies the Devonian to Mississippian Ouray Limestone (Elston, 1960, Table II; Parker and Roberts, 1963, Fig. 15; 1966, Fig. 15, Chart 1). In the area south of the Grand Canyon, the Redwall unconformably overlies the Devonian Martin Formation (Teichert, 1965, p. 16-18, Table 1; McKee and Gutschick, 1969, p. 18-23, Tables 3, 4).

On the Mogollon Rim, the Redwall Limestone locally onlaps two knobs of Precambrian Mazatzal Quartzite, named Christopher and Pine Islands (Teichert, 1965, p. 49). Because subangular cobbles of Precambrian quartzite have been described from the basal unit of the Redwall in the nearby Natural Bridge measured section (McKee and Gutschick, 1969, p. 677-678, Fig. 5, Pl. 2), these hills are thought to be remnants of post-Devonian erosion which stood as islands in the Redwall sea.

Walcott (1880, p. 222) was the first to recognize the unconformity at the base of the Redwall. He observed (p. 224) that "the Carboniferous rests on the slightly eroded surface of the Devonian formation." However, Noble (1922, p. 53) was "unable confidently to trace this unconformity in the region between Garnet Canyon and Cottonwood Creek and at all places to separate Devonian beds from the Redwall Limestone," and concluded that if an unconformity exists, "it is so obscure and exhibits so little irregularity that it can be detected only by obtaining determinable fossils in the strata within which it lies."
In the western Grand Canyon, McNair (1951, p. 518) identified the contact by the difference in color of the weathered surfaces, by an irregular erosion surface at the top of the Devonian beds, and locally, by angular blocks of Devonian limestone in the basal 0.6 to 3 m (2 to 10 ft) of the Redwall. At most western Grand Canyon localities, McKee and Gutschick (1969, p. 16, Table 2) noted the presence of an irregular surface or a basal conglomerate or both at the contact. In contrast, in the eastern Grand Canyon, no evidence of an erosion surface can be detected and the contact appears even and flat (McKee and Gutschick, 1969, p. 16, Table 2). The lack of erosional relief on the pre-Mississippian surface in the eastern Grand Canyon possibly resulted from a longer period of erosion there than places farther west (McKee and Gutschick, 1969, p. 16).

Where evidence of an erosion surface is lacking, the basal contact of the Redwall Limestone is difficult to identify. At the study area along South Kaibab Trail, the contact between dolomites of the Temple Butte Formation and those of the basal Whitmore Wash Member is impossible to locate precisely, but probably lies within a 1.62 m slope-forming covered interval (Appendix). The contact is concealed and the presence of an unconformity can only be assumed. Similarly, in measured stratigraphic sections along Grandview Trail, 10.5 km (6.5 mi) to the east of South Kaibab Trail and along Bright Angel Trail, 4.8 km (3 mi) to the west, McKee and Gutschick (1969, p. 617-619, 621-622) reported "unconformity assumed; not apparent in section."

The hiatus represented by the pre-Mississippian/Mississippian contact is generally considered to be a significant time interval, but
that belief is much influenced by the fact that the formations above and below represent different geologic systems (McKee and Gutschick, 1969, p. 14). The Temple Butte is currently assigned to the Frasnian Stage (lower Upper Devonian) based on a sparse fish fauna (McKee, in Poole et al., 1967, p. 887). Age diagnostic fossils from the basal beds of the Redwall indicate Kinderhook age in the western Grand Canyon and early to middle (?) Osage age in the eastern Grand Canyon. Thus, the faunal discontinuity shows a break in the rock record involving all of Kinderhook time in the eastern Grand Canyon, much of that time farther west, and possibly the latter part of Late Devonian time throughout the region (McKee and Gutschick, 1969, p. 54).

Whitmore Wash Member

The Whitmore Wash Member is the lowest of the four subdivisions of the Redwall Limestone. The type section is located "on the upthrown side of Hurricane Fault about 1/4 mile north of the Colorado River" (McKee, 1963, p. C21). At the type locality the Whitmore Wash consists of 31 m (101 ft) of very fine and even-grained dolomite in very thick beds. In most western and many northern Grand Canyon sections the Whitmore Wash is a limestone (McKee and Gutschick, 1969, Fig. 6) containing micrite, pisolites, peloids, bioclasts, and ooids in the upper parts of some sections.

The lower boundary, as previously discussed, does not always show evidence of the unconformity. Where an irregular surface is not present, the lower limit may be determined by other features (McKee and Gutschick, 1969, p. 24). These include contrasts in topographic
expression (a major cliff overlying a wide bench or series of ledges) and differences in lithology (thick-bedded brown dolomite over gnarly-bedded, sugary purple dolomite or thin-bedded cryptocrystalline laminated dolomite).

The upper boundary of the Whitmore Wash Member is placed where the alternating chert and carbonate of the Thunder Springs Member begins. This conformable surface is often expressed topographically as a flat, narrow ledge between two resistant cliffs (McKee and Gutschick, 1969, Pl. 2; Fig. 5). Where the bench is not observed the formation may form a continuous cliff, but the thick beds of the Whitmore Wash contrast sharply with the thin beds of the Thunder Springs.

The Whitmore Wash Member is 21 to 24 m (70 to 80 ft) thick in the eastern Grand Canyon, thickening to the northwest where it reaches a maximum of more than 61 m (200 ft) near the Arizona-Nevada line (Fig. 6). In the subsurface of northeastern Arizona its thickness is about 15 m (50 ft), thinning southward to zero near the Defiance-Zuni positive element.

Fossils are preserved in both limestones and dolomites of the Whitmore Wash Member. In the limestones, well-preserved fossils are relatively scarce, due most likely to post-burial destruction, but the fauna includes unbroken horn corals and brachiopods (especially spirifers), and crinoid fragments (McKee and Gutschick, 1969, p. 27). Fossils in the dolomites are sparse and localized, most apparently having been destroyed during dolomitization. In general, the fossils contained in these dolomites are preserved as external molds of horn corals, spirifers, crinoid fragments, and "tiny casts of undetermined
Fig. 5. Contact between Whitmore Wash Member and Thunder Springs Member.
Fig. 6. Isopach map of Whitmore Wash Member of northern Arizona. (From McKee and Gutschick, 1969).
fossils" (McKee and Gutschick, 1969, p. 30). Biostratigraphically significant brachiopods and foraminifers from basal beds of the Whitmore Wash have been determined as Kinderhook age in the western Grand Canyon and early to middle (?) Osage age in the central and eastern Grand Canyon.

In the study area along South Kaibab Trail, the Whitmore Wash Member is 26 m (86 ft) thick (Appendix). Here, the Whitmore Wash is composed of four lithologic units (base to top): 1) finely crystalline light gray dolomite, 2) finely crystalline dark gray calcitic dolomite with parallel and cross-laminations, 3) coarsely crystalline pale red calcitic dolomite, and 4) medium crystalline light brownish gray calcitic dolomite containing layers of nodular chert. The lower boundary is concealed in a covered interval where the unconformity is assumed to lie, and the upper limit is easily recognized by the narrow bench which forms at the Whitmore Wash-Thunder Springs contact (Fig. 5).

Thunder Springs Member

In western and central Grand Canyon sections, the Thunder Springs Member consists of chert alternating with thin beds of limestone, but in the eastern Grand Canyon the chert is interbedded with uniformly fine-grained dolomite. Its type section "is in the cliff of Redwall Limestone west of the springs at the head of Thunder River, about 2 miles north of the Colorado River in central Grand Canyon" (McKee, 1963, p. C21).
The upper boundary of the Thunder Springs Member is easily recognized in the field as a flat ledge or bench separating the thin-bedded carbonate and chert of the Thunder Springs from the overlying massive beds of the Mooney Falls Member (Fig. 7). This contact has been interpreted as a possible unconformity. Along the Hermit, North Kaibab, and Bass Trails, the contact shows evidence of slight erosion (McKee and Gutschick, 1969, Fig. 21a, 21f), but at most localities the contact is an essentially flat, even surface. According to McKee and Gutschick (1969, p. 55), the contact between the Thunder Springs Member and the Mooney Falls Member represents a surface of erosion over a wide area in the Grand Canyon region. McKee and Gutschick (1969, p. 55) concluded:

it is not clear whether this erosion was accomplished under subaerial or submarine conditions, but the lack of gravel and other reworked sediment and the general evenness of the surface suggest planation and gently scouring of unconsolidated sediment on the seafloor. A probable cause is relative lowering of base level or change in wave base that is inferred to have temporarily terminated deposition over a wide area.

At the type section the Thunder Springs Member is 42 m (138 ft) thick. In the western Grand Canyon the Thunder Springs is more than 30 m (100 ft) thick, and in the eastern Grand Canyon it is about 21 m (70 ft) thick (Fig. 8). The Thunder Springs reaches its maximum thickness of more than 91 m (300 ft) in southern Nevada, thinning to the southeast towards the Defiance-Zuni positive element at the northern part of the Arizona-New Mexico border.

Fossils are abundant in the Thunder Springs Member, with most occurring as external molds. Where molds are formed in chert, many delicate details of structure and ornamentation are preserved (McKee
Fig. 7. Contacts between Thunder Springs and Mooney Falls Members and Mooney Falls and Horseshoe Mesa Members.
Fig. 8. Isopach map of Thunder Springs Member of northern Arizona. (From McKee and Gutschick, 1969).
and Gutschick, 1969, p. 42). A semiquantitative study (McKee, 1960b) of the abundance and variety of fossils within the Thunder Springs elucidated three important trends. First, the abundance of all fossils increases greatly from east to west in the Grand Canyon region. Second, the variety of fauna increases in the same direction. Third, fossils of all types are very much more numerous in the chert than in the associated carbonate rock.

In the study area along South Kaibab Trail, the Thunder Springs is 26.5 m (87 ft) thick (Appendix). It is composed dominantly of medium light gray to pale red dolomite alternating with pinkish gray to white chert. Fossils preserved in the chert include molds of bryozoans, brachiopods, and crinoid fragments. The upper 2.5 m (8 ft) contains little or no chert, and the contact with the overlying Mooney Falls is expressed topographically as a narrow ledge (Fig. 7).

**Mooney Falls Member**

The type section of the Mooney Falls Member is located at Mooney Falls in Havasu Canyon, a major tributary of the Grand Canyon from the south (McKee, 1963, p. C22). The Mooney Falls Member is mainly composed of thick to very thick beds of limestone containing peloids, ooids, and bioclasts, but dolomite beds occur locally in the lower half of the member (McKee, 1963, p. C22). These coarse-grained limestones alternate with aphanitic limestone throughout the Mooney Falls, and zones of chert are characteristic of the upper part of the member (McKee and Gutschick, 1969, p. 59-61).
The upper boundary of the Mooney Falls Member can be determined based on lithologic differences, position of the uppermost chert unit, and change in type of bedding (McKee and Gutschick, 1969, p. 68). Lithologic differences are most often a change from the coarse-grained Mooney Falls limestones to the aphanitic limestones of the overlying Horseshoe Mesa Member. A prominent chert unit often marks the boundary, but the most consistent and reliable criterion is the change in bedding type (McKee and Gutschick, 1969, p. 69). In most sections the contact between the thick-bedded to massive Mooney Falls cliffs and the receding ledges of the thin-bedded Horseshoe Mesa is easily recognized (Fig. 7).

The thickness of the Mooney Falls Member averages slightly more than the combined thicknesses of the three other members (McKee and Gutschick, 1969, p. 56; Fig. 9). The Mooney Falls is about 61 m (200 ft) thick in the eastern Grand Canyon, thickening westward to more than 107 m (350 ft) in the western Grand Canyon. At its type locality the Mooney Falls is 95 m (312 ft) thick (McKee, 1963, p. C22). In the subsurface of extreme northeastern Arizona the Mooney Falls is less than 30 m (100 ft), thinning southward to zero near the Defiance-Zuni positive element.

Fossils of the Mooney Falls Member include brachiopods and solitary and colonial corals (McKee and Gutschick, 1969, p. 62). Foraminifers, mostly endothyrids, are numerous at many localities and serve as nuclei for some ooids. Crinoid ossicles are extremely common in places, but bryozoans are relatively rare compared to their abundance in the Thunder Springs Member (McKee and Gutschick, 1969,
Fig. 9. Isopach map of Mooney Falls Member of northern Arizona. (From McKee and Gutschick, 1969).
Much of the fossil material is preserved as fragments, suggesting that a larger and more varied fauna may have originally existed (McKee and Gutschick, 1969, p. 62). Age determinations of these fossils suggest that the Osage-Meramec boundary occurs at or near the top of the Mooney Falls (McKee and Gutschick, 1969, p. 30).

At the study area along South Kaibab Trail, the Mooney Falls is 74.5 m (244 ft) thick (Appendix). It consists mainly of fossiliferous micrite, crinoidal biosparrudite, and packed oosparite. In the lower part of the section crinoidal biosparrudite interfingers with fine-grained dolomite. At the top of the section, thin units of dark gray chert are present. The contact between the Mooney Falls Member and the overlying Horseshoe Mesa Member is an irregular surface, but this is a product of post-Redwall karstic erosion. The irregular surface is a channel 18 m (60 ft) wide and 1.8 m (6 ft) deep, filled with siltstone, mudstone, and unoriented blocks of banded chert all typical of the overlying Supai Group (McKee and Gutschick, 1969, p. 69). Thus, the channel is a result of post-consolidation solution, and not the result of a stratigraphic break at the boundary of the Mooney Falls and Horseshoe Mesa Members.

Horseshoe Mesa Member

The type section of the uppermost unit of the Redwall Limestone, the Horseshoe Mesa Member, is located at Horseshoe Mesa along Grandview Trail on the south side of the Grand Canyon (McKee, 1963, p. C22). The Horseshoe Mesa Member is composed dominantly of thin-bedded aphanitic limestone, but ooids, peloids, encrusting and

The Horseshoe Mesa Member is 38 m (125 ft) thick in northwestern Grand Canyon, thinning to 9 m (30 ft) at its type section in southeastern Grand Canyon (Fig. 10). The thickness of this unit has been greatly affected by pre-Supai erosion which "sculpted" the upper surface of the Horseshoe Mesa into a karstic topography (McKee and Gutschick, 1969, p. 72). Lenses of red mudstone within the Horseshoe Mesa are the result of Pennsylvanian or Permian sediments filling caverns and sinkholes in the Mississippian rock.

Fossils are uncommon in the Horseshoe Mesa Member. Brachiopods, pelecypods, corals, and foraminifers are found in local concentrations. McKee and Gutschick (1969, p. 73) suggested that the lime mud was "unfavorable for most forms of life and represented an environment largely devoid of current that would introduce shells or bioclastic grains." Corals indicate a Meramec age for the entire Horseshoe Mesa Member (McKee and Gutschick, 1969, p. 129).

In the study area along South Kaibab Trail, the Horseshoe Mesa Member is 20.85 m (68 ft) thick (Appendix). It is composed of thin-bedded oosparites and contains thin units of chert near the top.

**Upper Contact of the Redwall Limestone**

The irregular contact of the Redwall Limestone with the Watahomigi Formation, the basal formation of the Supai Group, records a long period of karstic solutioning and erosion based on stratigraphic age determinations. Local relief from 1 to 12 m (3 to 40 ft) is
Fig. 10. Isopach map of Horseshoe Mesa Member of northern Arizona. (From McKee and Gutschick, 1969).
apparent in some Grand Canyon sections; however, in most places the contact is flat and even, and does not appear to represent an important unconformity (McKee and Gutschick, 1969, p. 74, 76, Table 1).

The existence of the widespread unconformity was noted by Darton (1910, p. 13) and by Noble (1922, p. 61). Noble stated, "I have presented evidence that this surface is a plane of unconformity by erosion," and he revised the upper boundary of the Redwall based on this feature. Detailed descriptions of the Redwall-Supai contact in the Grand Canyon are provided by McKee and Gutschick (1969, p. 74-80) and McKee (1982, p. 39-40), and in the area south of the Grand Canyon by Huddle and Dobrolovny (1952, p. 88-90) and McKee and Gutschick (1969, p. 80-85).

In the Grand Canyon the Redwall is overlain by three types of strata (McKee and Gutschick, 1969, p. 76). In areas of low relief either conglomerate beds or lenses of conglomerate within gnarly-bedded limestone occur. Above these channel bottoms, red mudstones extend across the area. Where erosional remnants of Redwall projected higher topographically, the Redwall is in overlain by thin beds of Supai limestone.

The channel fills are of two general types (McKee and Gutschick, 1969, p. 76). Some channels contain large well-rounded cobbles and pebbles of chert and other durable materials that have been transported a considerable distance. These deposits probably occupy the channels of extensive drainage systems. The other type of channel fill deposit contains lenses of angular blocks of limestone or dolomite in a matrix of gnarly-bedded or structureless mudstones. These
channel fill deposits are interpreted as sediments occupying depressions of former sinkholes or solution channels (McKee and Gutschick, 1969, p. 76).

In the study area along South Kaibab Trail, sediments have infiltrated far below the upper surface of Redwall Limestone. Bedding planes in limestones approximately 6 m below the top of the Horseshoe Mesa Member have been filled with red Supai mudstone. Caves common in both the upper Mooney Falls and the Horseshoe Mesa Member contain breccia and mudstone from above.

In most places the hiatus between the Redwall Limestone and the Supai Group represents all of Late Mississippian time and the earliest part of Morrowan or Early Pennsylvanian time (McKee, 1982, p. 157). In the eastern Grand Canyon, rocks of Late Mississippian (Chesterian) age have been reported from Bright Angel Trail; however, in the western Grand Canyon pre-Supai buried valleys have been described. The oldest known fossils from the base of the Supai Group are younger than earliest Early Pennsylvanian (Morrowan) according to McKee (1982, p. 157).

**Pre-Supai Buried Valleys**

Recent observations in the western Grand Canyon revealed the presence of buried valleys in the Redwall Limestone, below the conglomerate at the base of the Watahomigi Formation (Billingsley, 1978, 1979; Billingsley and McKee, in McKee, 1982). These valleys average about 305 m (1000 ft) in width and 85 m (280 ft) in depth. A maximum depth of 122 m (400 ft) occurs near Quartermaster Canyon. The valleys are
part of an extensive drainage system which formed after Redwall deposition had ceased.

The valley-fill sequences are composed of four distinct types. These deposits can be correlated from section to section based on lithology, fossils, and rock color, but show considerable variation in thickness. Fossil evidence based on brachiopods, foraminifers, and spores indicates a Late Mississippian age for these deposits.

The basal unit in most valley-fill deposits consists of fluvial pebble and cobble conglomerates and calcareous sandstones. The upper marine units in the deposits generally consist of a massive, cliff-forming, thin-bedded limestone; calcareous sandstone and siltstone; and a thin unit of gray limestone (Billingsley and McKee, in McKee, 1982, p. 139).
REGIONAL CORRELATION

Age of the Redwall Limestone

The original 'Red Wall limestone group' of Gilbert (1875) and Marvine (1875) included the present day Redwall Limestone and an additional 518 m (1700 ft) of strata both overlying and underlying the Redwall. Gilbert (1875, p. 178) considered this thicker unit to be Carboniferous in general, containing fossils of Lower Carboniferous and Coal Measures age, and quite possibly including Devonian and Permian age strata. Walcott (1880, p. 224) described the 'Red Wall limestone' as having a fossil assemblage of "a few coal-measures species with a much larger proportion of a Lower Carboniferous character." Fossils from the "upper part of the Redwall in western Arizona" were determined by Meek and others to be from "an early portion of the Pennsylvanian" (Darton, 1910, p. 24) although the Redwall as a whole was considered by Girty (in Darton, 1910, p. 24-25) to be equivalent to the lower part of the Naco (Pennsylvanian) and Escabrosa (Mississippian) units of southeastern Arizona.

Redefinition of the Redwall Limestone by Noble (1922, p. 54) restricted the formation to limestones of Mississippian age. Fossil collections from Bass Canyon and near Bright Angel Trail studied by Girty, and from Hermit Trail studied by Schuchert, were identified as lower Mississippian (Noble, 1922, p. 56-57). Stoyanow (1936, p. 505,
517) regarded the Redwall as slightly older than the Escabrosa based on slightly different faunas in the two formations, but Huddle and Dobrovolny (1952, p. 86) suggested that the difference may perhaps be due to "incomplete collection and poor preservation rather than any real variation in age."

Chapters on foraminifera by Skipp, corals by Sando, bryozoans by Duncan, brachiopods by McKee and Gutschick, gastropods and pelecypods by Yochelson, cephalopods by Furnish, blastoids by Macurda, and crinoids by Brower (in McKee and Gutschick, 1969) provide detailed and comprehensive discussions of Redwall paleontology. Although many of the Redwall fossils are either local or long ranging and thus of little biostratigraphic value (Peirce, 1979, p. 215), the foraminifers, brachiopods, and corals are useful zone indicators.

Skipp (1969, p. 176, 179) reported that calcareous foraminifera in the Redwall range from late Kinderhook to middle(?) Meramec in age. Foraminifers in the Whitmore Wash Member are late Kinderhook to early and middle(?) Osage in age. Foraminifers are absent in the Thunder Springs Member, but this member is considered to be entirely Osage based on the ages of the enclosing strata. The Mooney Falls Member contains foraminifers ranging in age from middle(?) Osage to middle(?) Meramec. Foraminifers in the Horseshoe Mesa Member are sparse, with most specimens suggesting a middle Meramec age. A few Chester foraminifers were identified in the upper 1.8 m (6 ft) of the Horseshoe Mesa Member at Bright Angel Trail. According to Skipp (1969, p. 178-180), foraminiferal relations indicate that both the Mooney
Falls and the Horseshoe Mesa Members are progressively younger to the north and west in the Grand Canyon area.

Brachiopods examined by Dutro (in McKee and Gutschick, 1969, p. 435-436) are most numerous in the Thunder Springs and Mooney Falls Members, while the Whitmore Wash and Horseshoe Mesa Members contain few species and relatively few specimens. Brachiopods from the base of the Redwall in the northeastern and southwestern Grand Canyon are of Kinderhook age. Throughout the region brachiopods of early Osage to Meramec age have been recognized higher in the section. Chester age brachiopods have been reported from the uppermost Redwall beds along Bright Angel Trail.

Corals of the Redwall Limestone were studied by Sando (1964, 1969). In the Whitmore Wash Member corals are rare, and the Kinderhook-Osage boundary which occurs within the Whitmore Wash Member cannot be identified on the basis of coral faunas (McKee and Gutschick, 1969, p. 129). Corals in the Thunder Springs Member and the lower part of the Mooney Falls Member indicate an Osage age. For the upper Mooney Falls and the Horseshoe Mesa Members, corals indicate a Meramec age. The Osage-Meramec boundary, which occurs within the Mooney Falls Member, is essentially the same as that determined by foraminiferal zones (McKee and Gutschick, 1969, p. 129). No corals were found in the Chester age beds of the Bright Angel Trail section.

Recently, considerable refinement of age determination for the Redwall Limestone outside the Grand Canyon area has become possible based on detailed biostratigraphic studies. Mamet and Skipp (1970) investigated foraminifera of the Redwall in northern and central
Arizona. Purves (1978, p. 144-151) used the zonation scheme developed by Mamet and Skipp (1970) to correlate foraminifera of Mississippian strata in central and southeastern Arizona, and concluded that central Arizona foraminifera suggest Redwall deposition began somewhat later than that of the Escabrosa Limestone. Conodont biostratigraphy of the Redwall has been studied by Racey (1974) in east-central Arizona and by Walter (1976) in northwestern Arizona.

**Tectonic Setting**

During early Paleozoic time the western margin of the North American craton was flanked by the Cordilleran geosyncline. Deformation associated with the latest Middle Devonian to Early Mississippian Antler orogeny in the western United States divided the Antler foreland basin into a rapidly subsiding flysch trough adjacent to the Antler highlands, and the Deseret starved basin farther east along the edge of the cratonic carbonate platform (Gutschick, Sandberg, and Sando, 1980, p. 11; Sandberg and Gutschick, 1980, p. 128, Gutschick and Sandberg, 1983, p. 82, Fig. 2; Fig. 11). Early in Mississippian time, downbowing of the crust by the Antler orogeny caused sea level rise and transgression (the Haug effect of Johnson, 1971, 1972), and in response the carbonate platform began to prograde into the Deseret starved basin (Gutschick and Sandberg, 1983, p. 82). During short-term lowstands in sea level, these exposed platform sediments were subjected to solution and erosion (Gutschick et al., 1980, p. 112).

During the same period, the area between the Cordilleran geosyncline northwest of Arizona and the Sonoran geosyncline in
Fig. 11. Mississippian structural features of the United States. (From Gutschick and Sandberg, 1983).
southeastern Arizona was a mildly negative shelf that was intermittently invaded by marine waters (McKee, 1979, p. 199-200; Fig. 11) resulting in the deposition of Redwall and other Mississippian sediments. Mississippian carbonate strata deposited on this shelf have been subdivided into a lower depositional complex, comprising rocks of Kinderhook, Osage, and early Meramec ages, and an upper depositional complex, with rocks of middle Meramec through Chester age (Rose, 1976). Both sequences are carbonate sheets which thicken westward into the Cordilleran geosyncline. Within each sequence Rose (1976) recognized a carbonate platform, an ancient shelf margin, and a flysch trough. In northern Arizona and Nevada, the lower depositional complex contains a passive shelf margin between the Redwall-Escabrosa inner shelf to the east and the Deseret starved basin to the west. Although Rose (1976, p. 449) listed the entire Redwall as belonging to the lower depositional complex, Purves (1978, p. 23) noted that age determinations for the Redwall Limestone, based on foraminiferal studies by Mamet and Skipp (1970), would place part of the Horseshoe Mesa Member in the upper depositional sequence of Rose.

**Mississippian Shelves**

The passive shelf edge east of the Deseret starved basin has been the subject of intense study (Sandberg and Gutschick, 1977, 1979, 1980; Gutschick et al., 1980; Gutschick and Sandberg, 1983). Most recently, Gutschick and Sandberg (1983, p. 83-85) developed a six-part model for the recognition of this shelf edge based on lithofacies, rock colors and organic carbon content, coral and algae biofacies,
conodont biofacies, foraminifera and radiolaria biofacies, and trace fossil biofacies.

The Redwall-Escabrosa shelf (Fig. 11) is named for the carbonate formations deposited on it, the Redwall Limestone in northern Arizona and the Escabrosa Limestone in southern Arizona. The shelf extends eastward into southern New Mexico where it merges with the Lake Valley shelf and northward into Utah where it merges with the Madison shelf. The shallow-water limestones and dolomites of the Redwall-Escabrosa shelf are characterized by peloids, ooids, algae, calcareous foraminifera, bryozoans, and especially crinoids (Gutschick and Sandberg, 1983, p. 89).

An apparent symmetry of the Madison, Redwall-Escabrosa, and Burlington shelves relative to the axis of the Transcontinental arch (Fig. 11) has been noted by Gutschick and Sandberg (1983, p. 90). The similar stratigraphy and lithofacies of Upper Devonian and Mississippian rocks on the west, south, and east flanks of the Transcontinental arch led Gutschick and Sandberg (1983, Fig. 5) to connect the shelves around the southwest end of the Redwall-Escabrosa shelf. However, Gutschick and Sandberg (1983, p. 90) recognized that this interpretation of the paleogeography "is highly speculative in view of the paucity of information in northern Mexico and the complexity of its post-Mississippian history."

**Redwall-Escabrosa Carbonate Platform**

The Redwall-Escabrosa shelf was characterized by several major paleotectonic features (Fig. 12). A positive element or uplift,
Fig. 12. Paleotectonic features of the Redwall-Escabrosa shelf. From McKee, 1979.)
the Defiance-Zuni positive, was located in west-central New Mexico and east-central Arizona (McKee, 1951, p. 484, Pl. 1C; Huddle and Dobrovolny, 1952, Fig. 26; Kelley, 1955, Fig. 5; Wilson, 1962, p. 31; McKee and Gutschick, 1969, p. 572-573; McKee, 1979, Fig. 44; Gutschick and Sandberg, 1983, Fig. 5). The Defiance-Zuni positive has been called the Penasco Dome by Armstrong (1962, p. 14), but this newer name has only rarely been used (e.g. Kent, 1975, p. 9; Greenwood, Kottlowski, and Thompson, 1977, p. 1448-1449) because the term Defiance-Zuni is well-entrenched in the literature.

McKee and Gutschick (1969, p. 571) considered the Defiance-Zuni positive to have been one of the most significant structural features in Arizona throughout most of the Paleozoic and early Mesozoic Eras. Examination of isopach data and lithofacies trends led McKee (1979, p. 202, 203, p. 4-A) to suggest that the Defiance-Zuni positive remained emergent but low during deposition of the entire Redwall Limestone. However, it has been proposed that thinning of Mississippian strata at the Defiance-Zuni Positive may be the result of erosion caused by post-Mississippian uplift (Peirce, Keith, and Wilt, 1970, p. 47).

A prong, referred to as the Payson Ridge, extended southeastward from the Defiance-Zuni positive into central Arizona (McKee and Gutschick, 1969, p. 571-573; Racey, 1974, p. 21; Fig. 12). During deposition of the Whitmore Wash and Thunder Springs, these members "lapped against but did not cover" the Payson Ridge (McKee and Gutschick, 1969, p. 573). Distinct species of Thunder Springs corals on either side of the ridge give further evidence of a physical barrier
(Sando, 1969). The Payson Ridge was covered by sediment for at least part of the time of Mooney Falls deposition, but subsequent erosion has left an incomplete record (McKee and Gutschick, 1969, p. 573; McKee, 1979, p. 203, Pl. 9-5). Since the Horseshoe Mesa Member south of the Grand Canyon has been removed almost entirely by erosion, the effect of the Payson Ridge on sedimentation at that time is unknown (McKee and Gutschick, 1969, p. 573). Pine Island and Christopher Island, the Precambrian remnants subaerially exposed in Cambrian, Devonian, and some of Mississippian time, were located along the Payson Ridge.

Positive elements extending west and southwestward from the Defiance-Zuni positive have been recognized in many stratigraphic investigations and have been variously named. A summary of many of these is provided by Purves (1978, p. 24). McKee and Gutschick (1969, p. 571-573) described in detail the location and extent of the Peach Springs Ridge which extended westward from the Defiance-Zuni positive into northwestern Arizona. However, this feature is absent from a later discussion of Arizona paleogeography by McKee (1979). In southwestern Arizona and adjacent California and Mexico, Schuchert (1910, p. 470) designated a positive element "Ensenada Land". This concept has been retained by McKee (1951, p. 485; 1979, p. 205) although additional mapping and stratigraphic work in southeastern Arizona are needed to properly assess Mississippian paleotectonic elements of that region (Purves, 1978, p. 27).
Lithologic Correlation

Arizona

Mississippian formations in Arizona that are time-equivalent to the Redwall Limestone of northern Arizona are shown in Figure 13. In east-central Arizona around the Clifton-Morenci area (Lindgren, 1905a, p. 69; 1905b, p. 4) the Modoc Limestone is named for "170 feet of coarse blue or gray limestones with subordinate strata of quartzite and dolomite." Based on macrofaunal studies, Girty (in Lindgren, 1905a, p. 72) assigned a generalized Mississippian age for the Modoc Limestone. Later work on macrofauna by Stoyanow (1936, p. 511) restricted the age of the Modoc to Early Mississippian.

In southeastern, southern, and west-central Arizona, lower Mississippian strata are represented by the Escabrosa Limestone (Ransome, 1904; Hayes and Landis, 1965) and by the Escabrosa Group composed of the Keating and Hachita Formations in the Chiricahua Mountains of extreme southeastern Arizona (Armstrong, 1962). Macrofaunal studies of the Escabrosa Limestone indicate a Kinderhook to Osage age (Girty, in Ransome, 1904, p. 46-50; Williams, in Gilluly, Cooper, and Williams, 1954, p. 33-35; Sando, in Hayes and Landis, 1965, p. F24). The upper part of the Escabrosa Limestone contains possible Meramec strata (Williams, in Gilluly et al., 1954; Sando, in Hayes and Landis, 1965). The Escabrosa Group of extreme southeastern Arizona ranges in age from latest Kinderhook through late Meramec based on macrofauna and foraminiferal studies by Armstrong (1962, Fig. 1) and Zeller (1957, p. 685). The Keating Formation of the Escabrosa Group
Fig. 13. Lithologic correlation of Mississippian formations in Arizona. (From Purves, 1978).
ranges in age from latest Kinderhook through middle Osage, and the overlying Hachita Formation extends from middle Osage to late Meramec (Armstrong, 1962, Fig. 1).

Southern Nevada

Mississippian strata of southern Nevada are summarized in Figure 14. Formations equivalent to the Redwall Limestone are the Monte Cristo Limestone (Hewett, 1931, p. 17-21), now formally a group, southwest of Las Vegas, Nevada; the Rogers Spring Limestone (Longwell, 1928, p. 29-30) from the Muddy Mountains of southeastern Nevada; and the Joana Limestone (Spencer, 1917, p. 26) from near Ely, Nevada in the east-central part of the state.

The Monte Cristo Limestone as defined by Hewett (1931, p. 17-21) contained five members which are, in ascending order, Dawn Limestone, Anchor Limestone, Bullion Dolomite, Arrowhead Limestone, and Yellowpine Limestone. These members were elevated to formational rank and the Monte Cristo raised to group status by Langenheim et al. (1962, p. 601-603). Four of the formations of the Monte Cristo Group (all but the Arrowhead Limestone) are lithologically similar to and correspond well with the four members of the Redwall Limestone (McKee and Gutschick, 1969, p. 579).

The Monte Cristo Group has been assigned an Osage to Meramec age based on calcareous foraminiferal studies (Brenkle, 1973, Fig. 8). Subsequent biostratigraphic work by Pierce and Langenheim (1974) suggested that the Dawn Limestone through the lower Yellowpine Limestone range in age from Kinderhook to early Osage, and that a
Fig. 14. Lithologic correlation of Mississippian formations in southern Nevada. (From Purves, 1978).
hiatus separates the lower Yellowpine from the upper Yellowpine Limestone.

The Joana Limestone is considered to be of late Kinderhook to early Osage age on the basis of its fauna (Chillingar and Bissell, 1957, p. 2269). The Rogers Spring Limestone has also been demonstrated to be equivalent to the Redwall Limestone (McNair, 1951, p. 518; 1952, p. 49).

Southern Utah

Mississippian stratigraphic nomenclature in southern and north-central Utah has generally been derived from adjacent states (Purves, 1978, p. 59; Fig. 15). In south-central and southeastern Utah, Mississippian strata from the subsurface are assigned to the Redwall Limestone.

In southwestern Utah, lower Mississippian formations include the Monte Cristo Group and the Joana Limestone. The Monte Cristo Group was extended from southern Nevada into the Beaverdam Mountains of southwestern Utah by Langenheim (1963). The Joana Limestone was extended from Ely, Nevada into the Confusion Range of southwestern Utah by a number of workers (Campbell, 1951, p. 22-23; Zeller, 1957, p. 687-688; Chillingar and Bissell, 1957, p. 2269; Hose, 1963, 1965; Hose and Repenning, 1963; Johnson, 1971, Fig. 3). Between the Confusion Range of southwestern Utah and the Beaverdam Mountains of extreme southern Utah, Miller (1963, Fig. 2; 1966, p. 869) identified an informal lower unit (Kinderhook to Meramec) and upper unit (Chester) in strata of the Wah Wah Mountains. Farther to the east in the Star
Fig. 15. Lithologic correlation of Mississippian formations in southern Utah.

(From Purves, 1978).
Range, Mississippian carbonate strata are assigned to the Redwall Limestone (Baer, 1962, p. 33-34).

Formations in north-central Utah which are equivalent to the Redwall Limestone of northern Arizona are the upper part of the Upper Devonian to Lower Mississippian Fitchville Formation (Beach, 1961, p. 39; Rigby and Clark, 1962, p. 19), the Osage age Gardison Limestone (Morris and Lovering, 1961, p. 89), and the Osage to Meramec Deseret Limestone (Gilluly, 1932, p. 25-26).

West-central and southwestern Colorado

Mississippian formations of west-central and southwestern Colorado which have been correlated to the Redwall Limestone of northern Arizona are presented in Figure 16. In west-central Colorado the Leadville Limestone (Eldridge, in Emmons, Cross, and Eldridge, 1894; Johnson, 1945a,b; Hallgarth and Skipp, 1963; Nadeau, 1971, 1972; Conley, 1972; Craig et al., 1972) is equivalent to the Redwall Limestone. The Leadville Limestone of the Sawatch uplift area has been subdivided into three members which are, in ascending order, the Gilman Member (Tweto, 1949), the Radcliffe Member (Nadeau, 1971, p. 11), and the Castle Butte Member (Nadeau, 1971, p. 11, 15). In the White River Plateau area, the Leadville has been informally divided into a lower unit and an upper unit (Conley, 1972, p. 103, 107, 108, 111).

Foraminiferal studies indicate a middle to late Osage age for the Castle Butte Member (Halcomb, in Nadeau, 1972, p. 75, 111) and an early to late Osage age for the upper unit of Conley in the White River Plateau area (Skipp, in Conley, 1972, p. 108-109).
Fig. 16. Lithologic correlation of Mississippian formations in west-central and southwestern Colorado. (From Purves, 1978).
Mississippian strata in southwestern Colorado are assigned to the Redwall Limestone or the Leadville Limestone. The Leadville Limestone of the San Juan Mountains has been informally divided into a lower member (Kinderhook) and an upper member (early to middle Osage) by Baars (1966, p. 2093-2101) and Baars and See (1968, p. 344, 346). Elsewhere, microfossil studies by Mamet (in Armstrong and Mamet, 1976, p. 15) indicate a late Osage age for the Leadville Limestone, equivalent to the middle part of the Mooney Falls Member of the Redwall Limestone in northern Arizona.

Western New Mexico

Correlation of Mississippian formations of western New Mexico is shown in Figure 17. In extreme southwestern New Mexico the Escabrosa Group, composed of the Keating and Hachita Formations (Armstrong, 1962), is stratigraphically equivalent to the Redwall Limestone, although the upper Hachita Formation contains strata younger than the Horseshoe Mesa Member of the Redwall.

In central southwestern New Mexico, the Caballero Formation (Laudon and Bowsher, 1941, p. 2116-2117) and the overlying Lake Valley Formation (Cope, 1882, p. 158-159; Laudon and Bowsher, 1949, p. 10-15, Fig. 1) have been correlated to the lower Mississippian Redwall Limestone. Conodont biostratigraphic studies assign a Kinderhook age for the Caballero Formation (Lane, 1974) and an Osage (1964) or Osage to Osage-Meramec (Lane, 1974) age for the Lake Valley Formation.

In south-central New Mexico the Las Cruces Formation and the lower part of the Rancheria Formation in the Franklin and Hueco
Fig. 17. Lithologic correlation of Mississippian formations in western New Mexico. (From Purves, 1978).
Mountains are Redwall equivalents (Laudon and Bowsher, 1949; Lane, 1974, p. 269-270, Fig. 4). Conodont studies (Lane, 1974, p. 273) have yielded a late Osage to early Meramec age for the Las Cruces Formation. Age determinations for the Rancheria Formation range from Osage, based on intertonguing relationships with the Lake Valley Formation (Armstrong, 1962) to Meramec, as indicated by conodonts from a basal bed (Lane, 1974, p. 273).

The Kelly Limestone of west-central New Mexico (Armstrong and Mamet, 1976, p. 17) contains strata equivalent to the Redwall of northern Arizona. The Kelly Limestone is composed of two formal members, the lower Calosa Member and the disconformably overlying Ladron Member (Armstrong and Mamet, 1976, p. 18). Foraminiferal work indicates a late Osage age for the Calosa Member (Mamet, in Armstrong and Mamet, 1976, p. 18) and a later late Osage age for the Ladron Member (Armstrong and Mamet, 1976, Fig. 11).

In north-central New Mexico the basal formation of the Arroyo Penasco Group, the Espiritu Santo Formation (Baltz and Read, 1960), is equivalent to Mississippian strata of northern Arizona. The Espiritu Santo includes a basal sandstone, the Del Padre Sandstone of Miller, Montgomery, and Sutherland (1963). Both the Espiritu Santo and the Del Padre are considered of late Osage age (Armstrong and Mamet, 1974).

For subsurface work in the Four Corners area which includes extreme northwestern New Mexico, Redwall nomenclature has been successfully applied by Parker and Roberts (1963, p. 45; 1966, p. 2418), Johnson (in Craig et al., 1972, Fig. 1) and others.
CHERTS OF THE REDWALL LIMESTONE

The cherts of the Redwall Limestone can be separated into six general types (Fig. 18), based on both macroscopic and microscopic criteria. Macroscopic features include the size and shape of chert bodies, their contacts with surrounding host lithologies, surface textures, and color. Microscopic features are those revealed by petrographic examination of thin sections, such as the size, shape, and arrangement of crystals, mineralogic composition, and the presence or absence of allochems.

Chert types I and II are restricted to the Whitmore Wash Member; chert type III occurs throughout the Thunder Springs Member; chert types IV and V are present in the middle and upper Mooney Falls Member, respectively; and chert type VI is restricted to the Horseshoe Mesa Member.

Terms used here for the field description of chert morphologies include nodule, lens, and pseudobed. A nodule is defined as a chert body approximately 15 cm (6 in) wide, 15 cm (6 in) deep, and 30 cm (12 in) long, either in the form of a smooth oval or with an irregularly shaped outline. Lensoidal chert indicates smaller ovoid bodies, with average dimensions of 5 cm (2 in) wide, 5 cm (2 in) deep, and 15 cm (6 in) long. Pseudobedded chert forms laterally continuous layers of relatively uniform thickness from 5 to 15 cm (2 to 6 in) thick.
Fig. 18. Summary of six general types of Redwall chert.
Internal structures recognized in the field are laminations and banding. Laminations are layers usually 1 cm (0.4 in) thick or less that are parallel to bedding. Banding is layering at any angle to bedding. Concentric bands are common within one type of Redwall chert.

Petrographic terms used in this study to describe quartz textures are those generally accepted by most workers (e.g. Folk, 1980, p. 79). Megaquartz is composed of equant or elongated grains larger than 20 μm. Microquartz, comprising quartz grains 20 μm or smaller, is divided into two types, microcrystalline quartz and chalcedony. Microcrystalline quartz is formed of equant grains commonly 1 to 5 μm in diameter, but ranging from less than 1 μm to the arbitrary upper limit of 20 μm. Chalcedony is the fibrous variety of microquartz, with fibers varying from a few tens to hundreds of microns long. All chalcedony in this study is length-fast.

In addition to field and petrographic examination, the six chert types were analyzed by standard scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDXA), and X-ray diffraction (XRD) techniques. Petrographic terms used to describe quartz textures were extended to SEM/EDXA use based on size, shape, and mineralogic composition.

**Whitmore Wash Cherts**

Field Description

Two types of Whitmore Wash chert have been recognized within the Whitmore Wash based on distinctive morphologies and stratigraphic position. Chert type I, in the lower part of the section, is rare
and unevenly distributed. The chert occurs as isolated, irregularly shaped lenses approximately 5 cm (2 in) wide, 5 cm (2 in) deep, and 15 cm (6 in) long, elongated parallel or subparallel to bedding (Fig. 19).

Chert type II in the upper part of the Whitmore Wash Member consists of larger oval nodules which occur flattened in layers parallel to bedding (Fig. 20). The average distance between adjacent nodules is 30 to 50 cm (1 to 1.8 ft). These nodules commonly weather and erode more rapidly than the surrounding thick-bedded dolomite, leaving cavities in the rock.

Both types of Whitmore Wash cherts are white (N9), dull, porous, and soft, giving a "chalky" appearance to the weathered surface. Small crinoid ossicles and brachiopod shells are often silicified, while bryozoan fronds are typically preserved as molds in the chert. Some nodules also contain large patches of dolomite unreplaced by chert. No internal structure is present in these cherts.

Petrography

In thin section, the matrix of both types of Whitmore Wash chert is dominantly composed of equant microcrystalline quartz crystals with an average diameter of 1 to 5 μm. Sponge spicules and other small fossils are replaced by larger microcrystalline quartz averaging 10 to 15 μm across. Larger fossils exhibit a transition in crystal size from the microcrystalline quartz of the surrounding matrix to the drusy quartz and larger megaquartz crystals of the replaced fossil (Fig. 21).

The irregularly shaped lenses of chert type I contain chalcedony in addition to microcrystalline quartz and megaquartz. The
Fig. 19. Chert type I: Irregularly-shaped chert lens from the lower Whitmore Wash Member. Lens cap is 52 mm across.

Fig. 20. Chert type II: Ovoid chert nodules from the upper Whitmore Wash Member. Notebook is 19 cm long.
Fig. 21. Replacement textures typical of chert types I and II. Microcrystalline quartz and dolomite matrix; megaquartz replacement texture in crinoid. Crossed nicols, 100x.
length-fast chalcedony is present as a void-fill (Fig. 22). In one thin section a void rimmed by chalcedony was subsequently filled by megaquartz.

The large patches of coarse-grained dolomite included in chert type II and the larger megaquartz-replaced bioclasts of both chert types are sharply contrasted by the adjacent matrix of microcrystalline quartz or microcrystalline quartz and dolomite (Fig. 21). The subhedral to anhedral dolomite rhombs stained by Alizarin Red-S indicate slight dedolomitization.

**X-ray Diffractometry**

X-ray analysis of chert type I lenses yields only alpha quartz peaks. These chert samples are composed of microcrystalline quartz, chalcedony, drusy quartz, and larger megaquartz crystals. All, however, produce identical alpha quartz patterns because each component has the same mineralogic composition.

X-ray analysis of chert type II nodules reveals the presence of two mineral phases, alpha quartz and gypsum. Gypsum is not observable in thin section and the gypsum peaks are very low, suggesting that only a very small amount of gypsum is present. This small amount is probably close to the diffractometer detection limit of five percent.

In sample preparation the large unchertified areas of coarse-grained dolomite were selectively avoided. Dolomite intermixed with microcrystalline quartz in the matrix was not detected by X-ray; it apparently constitutes less than five percent of the sample.
Fig. 22. Chalcedonic void-filling cement in chert type I of the lower Whitmore Wash Member. Thin section courtesy of D. Sylvia. Crossed nicols, 100x.
SEM and EDXA Analysis

SEM examination of chert type I shows microquartz, micro-crystalline quartz, and chalcedony. The microcrystalline quartz crystals are blocky, with smaller crystals averaging 2 to 3 μm and larger crystals averaging 4 to 6 μm.

Fibers from a weathered surface containing chalcedony appear as unoriented straight rods. At high magnification these fibers show a surface texture consisting of a smooth rod with few (Fig. 23) or many (Fig. 24) small crystals attached to the rod surface. EDXA analysis of a single rod projecting into space (and thus isolated from the rest of the sample) yields a spectrum containing Si, Au, Pd, and Al peaks. The Au and Pd are from the material used to coat the sample, and the Al is from the sample holder stub. The rod and the crystallites contain Si and Ca and are probably chalcedony and calcite. A similar crystal habit for silica has been described for Pacific sediments cored by the Deep Sea Drilling Project (Hein, Vallier, and Allan, 1981, Pl. 15, Fig. 3).

SEM examination of a fresh fracture surface of the chert type II (Fig. 25) shows equant microcrystalline quartz crystals with an average diameter of about 1 μm, although crystal size ranges from 0.5 to 2 μm. In addition, extensive intercrystalline porosity is well-developed.
Fig. 23. Few calcite(?) crystallites on possible chalcedony rod from chert type I. SEM micrograph; scale bar = 5 \( \mu m \).

Fig. 24. Many calcite (?) crystallites on possible chalcedony rod from chert type I. SEM micrograph; scale bar = 5 \( \mu m \).
Fig. 25. Microcrystallite quartz texture of chert type II. Note extensive intercrystalline porosity. SEM micrograph; scale bar to left = 1 μm.
Thunder Springs Chert

Field Description

Chert type III from the Thunder Springs can be divided into four subtypes (IIIa, IIIb, IIIc, IIId) based on stratigraphic position and relationship of chert to host lithology. The first three subtypes are intergradational, and characterize chert in the lower, middle, and upper parts of the Thunder Springs Member, respectively. The fourth subtype is quite distinctive and serves as a marker unit 3.5 m (11.5 ft) below the top of the Thunder Springs Member.

Chert type IIIa, from the lower part of the Thunder Springs, is intermixed with the host lithology on a relatively fine scale because it contains a great amount of incompletely chertified host dolomite. Chert type IIIa pseudobeds are thinner (1 to 3 cm; 0.4 to 1.2 in), less laterally continuous, and more widely separated (5 to 10 cm; 2 to 4 in) than chert higher in the section, and thus account for a relatively smaller percentage of the total rock.

Chert type IIIb, in the middle part of the Thunder Springs Member, is somewhat thicker (5 to 10 cm; 2 to 4 in) and more laterally continuous. Chert type IIIb pseudobeds and host dolomite beds are more closely spaced (Fig. 26) and the chert shows more complete replacement than lower in the member. Here, chert comprises approximately one-half of the section.

Chert type IIIc pseudobeds from the upper Thunder Springs are the thickest found in the member. The 15 to 20 cm (6 to 8 in) thick chert pseudobeds are separated by 30 to 40 cm (1 to 1.25 ft) thick dolomite beds and comprise only about one-third of the section. These
Fig. 26. Chert type III pseudobeds and thin-bedded dolomite of the Thunder Springs Member. Hammer is 32 cm long.
cherts show almost complete replacement and are often highly fractured. In addition, these chert pseudobeds are usually laterally extensive, but can also terminate abruptly.

The fourth subtype, chert type IIId, is a distinctive marker unit within the upper part of the Thunder Springs Member. This chert is a single bed (25 cm; 10 in thick) of chertified crinoidal biosparrudite. Above the crinoidal biosparrudite are a 75 cm (2.5 ft) thick cherty (type IIIc) dolomite unit and a 2.5 m (8.2 ft) non-cherty dolomite unit which form the top of the Thunder Springs Member.

All cherts in the Thunder Springs are white (N9) to pinkish gray (5YR 8/1) on a fresh surface and weather light brown (5YR 5/6) to the dusky yellow brown (10YR 2/2) color of desert varnish. No internal structures are evident on fresh surfaces or on naturally etched weathered surfaces.

Fossils are abundant within Thunder Springs cherts. Most are preserved as detailed external molds best seen on weathered surfaces parallel to bedding. Crinoids are very common as individual ossicles, but some stems are fairly complete (Fig. 27). Bryozoan fronds and spiriferid brachiopods are also present. Fossils are generally much more abundant and better preserved in the chert than in the host dolomite (McKee, 1960b), although small horizontal tubes (Planolites?) are found only in the host carbonate near the bottom of the Thunder Springs Member.
Fig. 27. Crinoid stem mold in chert type III. Coin is 19 mm in diameter.
Petrography

In thin section, Thunder Springs cherts mimic the trend observed in the field of increasing separation of chert and dolomite towards the top of the section. At the bottom of the Thunder Springs Member, chert type IIIa is intimately mixed with dolomite or dolomite and calcite. Near the middle of the section, chert type IIIB and dolomite are still somewhat mixed. Towards the top of the Thunder Springs, chert type IIIc is completely separated from the host dolomite. A related trend demonstrated by these cherts is an increase upsection of chert pseudobed thickness.

Dolomite rhombs in the Thunder Springs Member are euhedral when surrounded by chert (Fig. 28) and subhedral to anhedral when bordered by other dolomite rhombs. Occasionally euhedral dolomite rhombs can be seen in the host lithology, especially near voids. Some dolomite rhombs stained with Alizarin Red-S are pink, indicating slight dedolomitization.

Fasicular calcite is present locally throughout cherts in the Thunder Springs Member. Examples from all parts of the section reveal that the fasicular calcite is a void-fill, often following a megaquartz void-fill stage.

Chert type IIId, the chertified crinoidal biosparrudite near the top of the Thunder Springs section, is as strikingly different in thin section as in the field. Within a single thin section crinoid ossicles are unchertified, completely chertified, and only partially chertified. Zoned megaquartz cement contains zoned quartz crystals
Fig. 28. Euhedral dolomite rhombs in microcrystalline quartz matrix of chert type III. Crossed nicols, 100x.
(Fig. 29), with growth lines clearly evident in both the cement and the crystals.

Fossil preservation is varied within the Thunder Springs Member. In the host dolomite, bryozoan fronds have unfilled or calcite-filled zoecia. In the cherts of the Thunder Springs, bryozoans contain megaquartz-filled zoecia. Bryozoans preserved in chert type IIIa have calcite in the walls, but in the upper part of the section (chert type IIIc), walls are usually completely replaced by silica. Many of the larger fossils are replaced by drusy quartz and larger megaquartz. Throughout Thunder Springs cherts, sponge spicules are replaced by drusy quartz, and larger fossils are replaced by drusy quartz and large megaquartz. Crinoid ossicles in host dolomite are partial dolomitized, while crinoid ossicles in cherts are partially dolomitized and partially chertified. Some chertified crinoid ossicles contain remnant calcite twin lines.

X-ray Diffractometry

X-ray analysis of chert type IIIa from the lower part of the Thunder Springs Member yields peaks for alpha quartz and dolomite only. Chert type IIIb from the middle of the section contains alpha quartz and dolomite, plus a small amount of calcite. In chert type IIIc, the chertified biosparrudite near the top of the Thunder Springs, only alpha quartz and calcite mineral phases are present. These results agree well with field and petrographic evidence. The decrease upsection of dolomite content within the cherts is demonstrated by an increase in the quartz-to-dolomite peak size ratio from the lower
Fig. 29. Growth lines in megaquartz and euhedral quartz crystals in chert type IIId. Crossed nicols, 100x.
(chert type IIIa) to the middle (chert type IIIb) part of the section, and the absence of dolomite in chert type IIIc from the top of the Thunder Springs Member. In addition, the minor amount of calcite from the middle of the section (chert type IIIb) is due to occasional single crystal fossil fragments or calcite-filled fractures. The calcite peaks identified in the chertified biosparrudite (chert type IIId) are from unchertified and partially chertified crinoid ossicles.

SEM and EDXA Analysis

SEM examination of chert types IIIa, IIIb, and IIIc reveals a fabric containing three distinct surface textures: large euhedral dolomite rhombs, small equant microcrystalline quartz, and an unidentified needle-like mineral (Fig. 30). The fibrous mineral is distributed in needle-rich (Fig. 31) and needle-poor patches. EDXA analysis of a single needle yields a spectrum containing Si, Au, and Pd peaks. The Au and Pd are from the material used to coat the SEM sample, and the Si is from the needle. Thus, EDXA analysis suggests that the needles are composed of silica.

Research devoted to SEM examination of chert and megaquartz textures has been the result of principally Deep Sea Drilling Project efforts (Heath and Moberly, 1971; von der Borch, Galehouse, and Nesteroff, 1971; Cook and Zemmels, 1972; Berger and von Rad, 1972; von Rad and Rosch, 1972; Heath, 1973; Lancelot, 1973; Garrison et al., 1975; Keene, 1975; Kelts, 1976; von Rad, Riech, and Rosch, 1978; Pisciotto, 1980; Hein, Vallier, and Allan, 1981). However, no example
Fig. 30. Silica needles (upper left) and large euhedral dolomite rhomb (lower center) in chert type III. SEM micrograph; scale bar to left = 10 µm.

Fig. 31. Silica needle patch in chert type III. SEM micrograph; scale bar = 1 µm.
of a similar needle-like texture in silica has been described by these authors.

Chert type IIId, the chertified biosparrudite, contains mostly medium sized (2 to 5 μm) equant microcrystalline quartz. Some larger (20 μm) microcrystalline quartz to megaquartz sized crystals have well-developed terminations.

**Mooney Falls Cherts**

Field Description

The two types of chert in the Mooney Falls Member are characterized by a very different appearance and stratigraphic position. Chert type IV occurs in the middle of the Mooney Falls Member and is very rare. Chert type IV is composed of incompletely chertified, laterally discontinuous, and irregularly shaped nodules 30 to 40 cm (1 to 1.25 ft) long that are flattened parallel to bedding (Fig. 32).

At the top of the Mooney Falls Member is chert type V, a stratigraphically important type of chert. This laterally continuous lensoidal chert unit serves to demarcate the Mooney Falls and Horseshoe Mesa Member boundary where other criteria are ambiguous or lacking (McKee and Gutschick, 1969, p. 58; Fig. 33).

On a fresh surface, chert type V is light olive gray (5Y 6/1) to medium dark gray (N4), alternating in concentric bands (Fig. 34). Most samples exhibit a dusky yellow brown (10YR 2/2) weathering rind (Fig. 34).
Fig. 32. Irregular chert nodule of chert type IV, middle Mooney Falls Member. Lens cap is 52 mm across.
Fig. 33. Chert type V: lensoidal chert from the top of the Mooney Falls Member.
Fig. 34. Concentric banding and weathering rind in chert type V. Lens cap is 52 mm across.
Petrography

Cherts in the Mooney Falls Member are principally composed of microcrystalline quartz crystals (1 to 8 μm in diameter), larger microcrystalline quartz to small megaquartz sized crystals (15 to 30 μm), and larger megaquartz (50 to 175 μm) crystals. Hematite is present as equant grains 3 to 10 μm in diameter which coat peloids and most bioclasts. Small angular hematite crystals (6 μm long and 1 μm wide) are trapped between megaquartz crystals of cements and replaced fossils. Calcite occurs as minute inclusions in megaquartz, as large unreplaced single crystal bioclasts, and as irregular patches within microcrystalline quartz matrix. Organic matter is dark brown in plain light and locally concentrated.

The rare nodules of chert type IV in the middle part of the Mooney Falls Member contain microcrystalline quartz with irregular patches of single crystal calcite and smaller individual calcite crystals. No fossils are evident in this chert.

Chert type V, the dark gray concentrically banded chert which occurs at the top of the Mooney Falls, shows much original texture. Internal structure seen in hand sample is composed of darker gray bands rich in organic matter and lighter gray bands with little organic matter (DeCelles and Gutschick, 1983, Fig. 7).

These gray chert lenses contain a great variety of bioclastic material within a large microcrystalline quartz to small megaquartz sized matrix (15 to 30 μm). Sponge spicules and foraminifera are filled with larger microcrystalline quartz to small megaquartz. The foraminifers are usually associated with peloids or other fossils such
as ostracodes. Ostracodes, however, are found in non-peloidal microfacies as well, and always contain megaquartz-filled intraparticle voids. In some areas peloids have been partially replaced by microcrystalline quartz and are cemented with megaquartz. Crinoid ossicles are replaced by small megaquartz crystals around the edges and by larger megaquartz crystals toward the center of the ossicle or entirely by large microcrystalline quartz to small megaquartz sized crystals.

Fractures within chert type V are of three kinds. Calcite-filled fractures are usually only 3 μm wide. Hematite-filled fractures are approximately 25 μm wide and are very continuous. Fractures filled by megaquartz with calcite inclusions are often widest, about 100 μm, but taper quickly.

The dusky yellow brown rind of chert type V contains large patches of calcite which have been leached to the outer surface of the chert by weathering processes.

X-ray Diffractometry

Chert type V, the concentrically banded gray chert of the uppermost Mooney Falls Member, contains only alpha quartz and calcite in diffractometer traces. Alpha quartz is predominant (85%) and calcite is subordinant (15%), as estimated from relative peak intensity.

These X-ray diffractometry results agree well with petrographic observations. Microcrystalline quartz and megaquartz both yield an alpha quartz pattern. Calcite, present in thin section as minute
inclusions in megaquartz and as rare irregular patches and fractures, is only a small percent of the whole rock sample.

SEM and EDXA Analysis

The concentric banding so visible in hand samples and thin sections of chert type V was not found with scanning electron microscopy at very low SEM magnification. At higher magnifications, variations in microcrystalline quartz texture are apparent but no banding patterns are discernable. The very small, equant microcrystalline quartz crystals are light colored in the micrographs, contrasting with the larger intermixed calcite crystals which appear dark. At still higher magnification the range in microcrystalline quartz crystal size is easily recognized (Fig. 35). Thus, SEM examination revealed no textural differences related to banding in chert type V.

In addition, EDXA analysis showed no compositional difference between the lighter and darker bands. Spectra for microcrystalline quartz obtained by EDXA analysis contain only Si, Au, and Pd peaks; the latter two peaks are from the material used to coat the SEM samples. Elements lighter than Na are unseen by EDXA, so organic matter, identified petrographically as the source of the coloration in the bands, is not recorded by EDXA analysis.

Horseshoe Mesa Cherts

Field Description

In the Horseshoe Mesa Member, chert type VI occurs in the top 5.5 m (18 ft) of the member, above a 15.5 m (51 ft) thick non-cherty section of the Horseshoe Mesa Member. The cherty part of the Horseshoe
Fig. 35. Variation in microcrystalline quartz crystal size typical of chert types IV and V. SEM micrograph; scale bar to left = 8 μm.
Mesa Member can be subdivided into two units based on chert features, a lower unit 4 m (13 ft) thick containing chert type VIa and an upper unit 1.5 m (5 ft) thick containing chert type VIb (Fig. 36).

Chert type VIa (Fig. 36) is composed of pseudobeds 20 to 30 cm (8 in to 1 ft) thick separated by host peloidal limestone beds 40 to 50 cm (1.25 to 1.75 ft) thick. The pseudobeds are of uniform thickness and are very continuous laterally.

Chert type VIb (Fig. 36) contains small lenses of chert 2 to 5 cm (.8 to 2 in) wide and 10 to 15 cm (4 to 6 in) long that are flattened parallel to bedding. In some places the lenses have coalesced into very thin pseudobeds. The lenses and thin pseudobeds are laterally extensive. Chert type VIb forms a much smaller percentage of the total rock than chert type VIa.

Chert type VI is white (N9) with light gray (N7) internal laminations (Fig. 37). Most chert bodies are much more intensely fractured than the surrounding host limestone. No fossils were identified from either chert type VIa or chert type VIb.

Petrography

Chert type VI is composed of very fine-grained microcrystalline quartz (2 μm), coarse-grained microcrystalline quartz/small megaquartz (15 to 30 μm) crystals, and megaquartz. Megaquartz is present as either large crystals (100 to 125 μm) with growth lines or as smaller drusy crystals. Hematite is found as equant, subrounded crystals 6 to 12 μm in diameter or as angular crystals up to 3 μm long and less than
Fig. 36. Chert type VI showing lower pseudobedded unit and upper lensoidal to pseudobedded unit of Horseshoe Mesa Member. Hammer is 32 cm long.
Fig. 37. Parallel laminations in chert type VI. Lens cap is 52 mm across.
Laminations visible in the field are easily seen in thin section (Fig. 38). White chert is light colored in thin section and gray chert is dark colored. The dark color is due to concentrations of organic matter (DeCelles and Gutschick, 1983, Fig. 7).

Both the white chert and the gray chert contain peloids and calcispheres. The peloids are round (80 to 150 μm in diameter) or oval (50 to 80 μm wide, 180 to 300 μm long). In the white chert, peloids are partially replaced by very fine-grained microcrystalline quartz with calcite inclusions. Peloids in the gray chert are often completely replaced by small megaquartz crystals containing calcite inclusions. Angular hematite crystals are trapped between megaquartz crystals. Peloids in both cherts are surrounded by equant hematite crystals which coat the outer surfaces of the peloids.

Calcspheres in the cherts are 100 to 150 μm in diameter and are filled by small megaquartz crystals with minute calcite inclusions. Hematite is present as small angular crystals between megaquartz crystals and as equant grains which coat the calcspheres.

The allochems, including possible sponge spicules, are distributed in microcrystalline quartz crystals 5 to 15 μm in diameter. Megaquartz crystals have calcite inclusions, and small irregular hematite crystals trapped at their crystal boundaries.

The two types of fractures in chert type VI cross both white chert and gray chert. Quartz-filled fractures are small, thin, and irregularly shaped. The fractures are typically 30 to 50 μm wide and
Fig. 38. Dark brown organic matter concentrations in laminated chert type VI. Plain light, 35x.
the small megaquartz crystals which fill them are 25 to 35 µm in diameter. Larger quartz- and calcite-filled fractures are 250 to 500 µm wide. These are filled first by drusy to larger megaquartz crystals with growth bands which line the fracture walls. The remainder of the fractures is filled by large blocky calcite crystals having well-developed twin lines. In some places irregularly shaped calcite in optical continuity with the blocky crystals has replaced the microcrystalline quartz matrix surrounding the fracture.

**X-ray Diffractometry**

X-ray diffraction of a whole rock sample of chert type VI yields peaks corresponding to alpha quartz and calcite. Although quartz is the dominant mineral, calcite forms a fairly large percentage of the total rock composition relative to most cherts in this study. This greater amount of calcite is due to the large calcite-filled fractures within the chert that are easily seen in hand sample and thin section.

**SEM and EDXA Analysis**

SEM microscopy of chert type VI (Fig. 39) reveals no difference in texture between the white chert and the gray cherts. Cherts of both colors have a very fine-grained microcrystalline quartz component and a coarser microcrystalline quartz/fine megaquartz component. Most of the very fine-grained microcrystalline quartz crystals average 0.20 to 0.25 µm in diameter. EDXA spectra were not obtained for these samples, since organic matter is not recorded by EDXA techniques.
Fig. 39. Variation in microcrystalline quartz texture of chert type VI. SEM micrograph, scale bar = 1 μm.
Diagenetic History of Redwall Cherts

Field relations of chert and host carbonate in the Redwall Limestone clearly suggest an early diagenetic or penecontemporaneous replacement of the chert before lithification (McKee, 1960b; McKee and Gutschick, 1969, p. 114). McKee (1960b) examined four-foot (1.2 m) square plots in vertical outcrops of the Thunder Springs Member to determine patterns of chert distribution and the location and type of all fossil material. The chert pseudobeds studied by McKee are flat and evenly bedded when viewed at a distance. However, close examination revealed that the top and bottom surfaces are highly irregular and that entire pseudobeds can terminate laterally within short distances. The irregular nature of these chert contacts with the host carbonate and the presence of irregular patches of carbonate within chert bodies argue strongly in favor of a replacement origin of the chert (McKee and Gutschick, 1969, p. 113-114).

External molds in the chert show much better preservation of delicate details of shell structure than molds in the host dolomite. Therefore, McKee (1960b, p. B463) postulated that chertification of the Redwall occurred very early in its diagenetic history, prior to dolomitization. Additionally, McKee (1960b) noted that in every sample plot fossils were more numerous in the chert than in the host carbonate and speculated that locally abundant fossils may have formed zones of maximum permeability and were therefore zones most favorable for chertification. McKee and Gutschick (1969, p. 560) considered an alternative possibility, that zones of high organic decomposition controlled the distribution of chert within the Redwall. However, Kent
(1975, p. 68) interpreted the association of fossils with cherts as a consequence of better quality fossil preservation in chert than in dolomite.

Two separate lines of field evidence help to further substantiate an early diagenetic or penecontemporaneous origin of the cherts. First, chert pebbles distributed locally in basal beds of the Supai Group were derived, in part, from the Redwall Limestone of adjoining areas (McKee and Gutschick, 1969, p. 560). This suggests that chert formation occurred before Middle Pennsylvanian time. Second, at Sycamore Canyon layers of nodular chert in the upper Whitmore Wash Member (chert type II) are highly contorted and in places broken by small faults with 2.5 to 7.5 cm (1 to 3 in) displacement (McKee and Gutschick, 1969, p. 113, Fig. 11b), while limestone beds above and below are unaffected. Similar folds in the Thunder Springs Member (chert type III) are found at Havasu Canyon (McKee and Gutschick, 1969, p. 113, Fig. 21g). From these structures, McKee and Gutschick inferred penecontemporaneous deformation of firm silica masses in soft carbonate sediment.

Petrographic examination of the Redwall Limestone (McKee and Gutschick, 1969, p. 113; J. Smith, 1974, p. 58; Kent, 1975, p. 67-68; Purves, 1978, p. 165; this study) provides numerous examples of early replacement textures within cherts. Many of the microscopic replacement textures are similar to megascopic features seen in the field. Irregular patches of chert in host carbonate, "islands" of limestone or dolomite in chert, and intertonguing and embayment of one rock type
More recent studies have supplemented the original observations of McKee and Gutschick (1969). J. Smith (1974, p. 58) noted that delicate internal structures of various fossils were preserved within chert, probably soon after deposition. Kent (1975, p. 67) observed that "tripolitic" chert, described as a mixture of chert and carbonate minerals, graded into "massive" chert, defined as the complete replacement of host rock by silica. Purves (1978, p. 165) reported silicification of fossil allochems, silicified pseudomorphs after calcite, silicified laminae, and siliceous etching into euhedral calcite crystals as common replacement textures in Redwall cherts.

In previous investigations (McKee and Gutschick, 1969, p. 559-560; Kent, 1975, p. 68; Purves, 1978, p. 156, 165) the typical paragenetic sequence observed was chertification, followed by dolomitization. Detailed examination of chert thin sections suggests that such a paragenetic sequence is oversimplified and incomplete. Instead, a four-step diagenetic history (Fig. 40) is proposed: 1) a small amount of the original allochems and lime mud, dominantly composed of calcite, is replaced by euhedral dolomite rhombs; 2) chertification follows, during which much of the sediment can be replaced by chert; 3) wholesale dolomitization of remaining carbonate produces dolomite rhombs which are typically subhedral to anhedral except near voids, where they are often euhedral; and 4) dedolomitization.

Chert microfacies contain their own subset of diagenetic events (Fig. 40). Microcrystalline quartz replaces lime mud, a process
### Fig. 40. Summary of diagenetic events in Redwall Limestone cherts. 

MCQ = microcrystalline quartz, CH = chalcedony, MQ = megaquartz, WS = wholesale.

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first suggested for the Redwall by McKee and Gutschick (1969, p. 113), and can replace various allochems as well. Length-fast chalcedony is present as a pore-filling cement. Megaquartz, a post-chalcedony pore-filling cement, also replaces allochems.

If chertification is not complete, patches of calcite are surrounded by chert. During chertification small, thin-shelled fossils are very susceptible to replacement and are usually completely replaced. Crinoids, composed of single crystals of calcite, are often only partially replaced, while dolomite rhombs remain completely unreplaced by chert.

Although all of these steps rarely occur in a single sample, the diagenetic sequence of events is consistent throughout all thin sections and the order of events is never reversed or mixed. Chert type I is incompletely chertified, containing microcrystalline quartz, chalcedony, megaquartz, and dolomite in a dolomite host rock. Chert type II has undergone some dolomitization, a chertification stage yielding microcrystalline quartz and megaquartz, wholesale dolomitization, and slight dedolomitization. Chert type III shows evidence of an initial dolomitization stage, increasingly complete chertification (by microcrystalline quartz, silica needles, and megaquartz) upsection, wholesale dolomitization, and slight dedolomitization. Chert type IIIId also contains original calcite from crinoid ossicles. Chert type IV is incompletely chertified by microcrystalline quartz and megaquartz, and contains large patches and small single crystals of calcite. Chert types V and VI are composed of microcrystalline quartz and megaquartz and are completely chertified.
MODEL FOR CHERTIFICATION

Geologic occurrences of chert are often separated into three distinct groups based on different types of stratigraphic and tectonic settings: 1) nodular chert in cratonic carbonate rock, 2) pure, bedded chert in geosynclinal tectonic regions, and 3) chert associated with hypersaline lacustrine deposits (Pettijohn, 1975, p. 401; Blatt, 1982, p. 380). Redwall Limestone cherts, formed in shallow shelf carbonates, clearly belong to the first category. As already mentioned, genetic models developed to explain the replacement of limestone by chert must address the basic questions of silica source, diagenetic timing, and diagenetic environment of chertification (Meyers, 1977, p. 76). Evidence for the timing of chertification of the Redwall Limestone was presented in the previous chapter; silica source and diagenetic environment of chertification are the subject of the following sections.

Silica Sources

Potential sources of silica for chert formation may be inorganic, biogenic, or a combination of both. Inorganic sources include silica-bearing hydrothermal fluids, degradation of marine volcanic debris, and subaerial weathering and erosion of a land mass. An older view, now largely discounted, is that nodular chert may form inorganically by direct precipitation of silica gel on the sea floor (Tarr, 1926). Biogenic silica sources are radiolarians (Cambrian to Recent)
and diatoms (Triassic to Recent) in deeper water pelagic limestones, and sponge spicules (Cambrian to Recent) in shallow shelf carbonates. Silica sources which combine inorganic and biogenic processes are inorganic precipitation of silica derived indirectly through plankton blooms induced by submarine volcanism, and oceanographic upwelling of deep sea water enriched in silica by radiolarians.

Nonetheless, agreement does not exist among workers on the relative importance of various silica sources. In particular, Laschat (1984, p. 257) stated that biogenic silica cannot be considered as the primary silica source because chert formation can take place without the presence of biogenic silica. Further, Laschat (1984, p. 257) argued that dissolved silica resulting from chemical weathering is the main silica source in chert formation.

Laschat's view does not seem to be upheld by the majority of investigators. A biogenic source for deep sea cherts in pelagic limestone host rocks is now generally accepted, while the source of silica in deep sea cherts in black shales is still unknown (Davies and Supko, 1973, p. 381). Wise and Weaver (1974, p. 301) concluded that biogenic silica is by far the most important immediate silica source for oceanic cherts. The source of silica for chert nodules in shallow shelf limestones is also generally considered to be biogenic, with siliceous sponge spicules often supplying the silica (e.g. Wilson, 1966, p. 1048; Meyers, 1977, p. 81-85).

The source of silica for Redwall cherts has been debated by numerous workers. McKee and Gutschick (1969, p. 112-114, 559-561) ruled out a hydrothermal origin because its localized character could
not account for the widespread distribution of the chert. A marine volcanic source was rejected because no evidence of Mississippian volcanism in the region has been proposed. Instead, McKee and Gutschick proposed two possible sources of silica: 1) upwelling of silica-rich deep sea water into a zone of low silica water, or 2) fluviatile introduction of silica produced by subaerial erosion of a low-lying land mass. Regarding these two possibilities, McKee and Gutschick (1969, p. 560) stated, "The immediate source of silica may have been either adjacent to the shore where streams were emptying fresh water into the sea or far to seaward where upwellings from deeper parts of the sea were reaching the shelf."

J. Smith (1974, p. 59) discarded McKee and Gutschick's hypothesis that silica-rich river water could have provided the necessary silica because the paucity of detrital material seemed to Smith to preclude that explanation. However, Smith's objection may be unwarranted if the silica was carried in solution. Smith (1974, p. 59) envisioned silica being introduced along the shelf of the Mississippian miogeosyncline by upwelling of deep, radiolarian-enriched waters. According to Smith, these large upwelling currents along the Mississippian shelf would explain the widespread distribution of chert type III in the Thunder Springs Member.

Kent (1975, p. 73-75) suggested a combination of marine volcanism and J. Smith's (1974, p. 59) upwelling hypothesis. In this view, upwelling currents enriched in silica by submarine volcanism would provide silica for biogenic blooms of siliceous organisms. Kent's hypothesis is similar to that described by Berner (1971), and
submarine volcanism in Cordilleran areas has been reported by Bissell (1959). Further, Kent speculated that his hypothesis would account for the alterations of chert type III and host carbonate seen in the Thunder Springs Member. During periods of maximum volcanism, abundant silica would be introduced and siliceous organisms would flourish, producing the chert pseudobeds. During periods of quiescence, silica would be scarce and populations of siliceous organisms would wane, producing the host carbonate layers.

Purves (1978, p. 163-167) identified three types of genetically similar cherts: wave base chert, eustatic chert, and near-shore chert. Wave base chert derived silica from indigenous siliceous sponge spicules. Eustatic chert resulted from shoreline redistribution and mechanical concentration of siliceous sponge spicules. Near-shore chert, a very rare type, apparently formed by dissolution and reprecipitation of siliceous clastics.

In this study, siliceous sponge spicules have been observed petrographically in many Redwall cherts. Petrography of the Redwall sponge spicules implies that they served as a silica source. Modern sponge spicules are composed of biogenic opal-A and contain a well-developed axial canal. The Redwall sponge spicules show evidence of at least a three-step diagenetic sequence: dissolution of the original biogenic silica, a moldic stage when definition of the central canal was lost, and subsequent fill of the entire mold by small megquartz crystals. Chert types I and II in the Whitmore Wash contain both monaxon and tetraxon (Fig. 41) spicules. Monaxon sponge spicules occur throughout chert type III of the Thunder Springs Member. In
Fig. 41. Tetraxon sponge spicule in chert type I. Thin section courtesy of D. Sylvia. Crossed nicols, 35x.
chert type V of the uppermost Mooney Falls Member, sponge spicules are present and in some places are locally abundant (Fig. 42). Questionable sponge spicules have been identified from chert type VI of the Horseshoe Mesa Member. The nearly ubiquitous distribution of sponge spicules in these cherts suggests that an adequate indigenous silica source was available to Redwall carbonate sediments during chertification.

**Diagenetic Environment of Chertification**

The diagenetic environments in which chertification can take place are poorly understood despite nearly a century of chert investigation. Recent Deep Sea Drilling Project studies have added much to current knowledge of geologically young cherts in pelagic sediments but have not been directed towards characterizing cherts in ancient shallow shelf carbonates.

However, two studies of chertification in shallow carbonate environments serve as models for identifying processes by which chertification may occur. The mixing zone chertification model constructed by Knauth (1979) outlines the thermodynamic and physical conditions under which limestone may be replaced by chert. The chert microfacies model developed by Meyers (1977, p. 100-102) details paragenetic sequences of chert fabrics observed in thin section. A combination of these models is proposed to explain the origin of chert in the Redwall Limestone.

In the mixing zone model (Fig. 43), chert replacement of limestone occurs in mixed marine-meteoric coastal systems. Dissolution
Fig. 42. Monaxon sponge spicule in chert type V. Thin section courtesy of D. Sylvia. Crossed nicols, 35x.
Fig. 43. Mixing zone model for chertification of the Redwall Limestone. (After Knauth, 1979).
of biogenic silica as opal-A, and the mixing of marine and fresh waters produce waters highly supersaturated with respect to quartz and undersaturated with respect to calcite and aragonite (Knauth, 1979, p. 274).

Subaerial sediments containing abundant carbonate and biogenic silica debris are deposited by large tides or storms. Meteoric water percolating through these sediments quickly becomes saturated with respect to calcite by dissolution of aragonite and magnesian calcite. At the same time, concentrations of biogenic silica rise and approach saturation levels as the mixing zone is encountered. Continued mixing with silica-undersaturated sea waters lowers silica saturation levels. Thus, maximum silica concentration occurs within the mixing zone.

The mixing of meteoric and marine waters saturated with respect to calcite can produce a zone of waters undersaturated with respect to calcite if the two waters have either different CO2 partial pressures or different temperatures (Knauth, 1979, p. 275). Ground water in the mixing zone can thus be simultaneously supersaturated with respect to quartz and opal-CT and undersaturated with respect to calcite. In such a mixing zone, chert would replace limestone.

Several lines of evidence support the mixing zone model for chertification. First, an indigenous silica source in the form of siliceous sponge spicules was readily available, as shown by their presence within chertified sediment. Sponge spicules are almost ubiquitous in Redwall cherts and show evidence of being replaced by megaquartz following a void stage rather than having been directly recrystallized from biogenic opal-A to megaquartz.
Second, the stratigraphic distribution of the various geometries of Redwall chert bodies is consistent with this model. Chert types II, III, V, and VI are laterally extensive and occur throughout the Grand Canyon. Chert types I and IV, which are rare and irregularly spaced within any given stratigraphic section, are also widely distributed within Grand Canyon exposures. The laterally extensive chert type III pseudobeds of the Thunder Springs Member are probably the result of a laterally extensive mixing zone; on the Yucatan Peninsula of Mexico the mixing zone covers an area of many thousands of square kilometers (Back and Handshaw, 1970).

Third, the close association of dolomitization with chertification in the Thunder Springs Member argues strongly for a mixing zone diagenetic environment. Paleogeographic evidence favors a model of dolomitization within the Redwall by mixing of marine and meteoric waters; shelf carbonates tend to be exposed during regression and become sites for fresh water recharge and mixed water dolomitization (Morrow, 1982, p. 100).

Finally, geochemical data support a mixing zone model for chertification. Stable isotope studies of nodular and bedded chert by Knauth (1973) and Knauth and Epstein (1976) included two samples of chert type III collected at the top of the Thunder Springs Member along South Kaibab Trail. Hydrogen and oxygen stable isotope compositions indicate "a significant meteoric water component" (Knauth, 1985, pers. comm.) for the Thunder Springs Member chert.

The microfacies model of Meyers (1977, p. 100-102) describes a paragenetic sequence of chert fabrics found in a Mississippian
shallow shelf carbonate unit of New Mexico. Meyers (1977, p. 100-102) reasoned that solubility differences between biogenic opal-A of sponge spicules and crystalline secondary silica were the main driving force of chertification because diagenetic silica phases have much lower solubilities than biogenic opal-A.

In the microfacies model, siliceous sponge spicules composed of opal-A dissolve during burial. Pore waters become supersaturated with respect to cristobalite and quartz. Precipitation of opal-CT keeps the solution undersaturated with respect to amorphous silica. Opal-CT precipitated in micropores grows and coalesces to replace lime mud and skeletal fragments. Most of the opal-CT recrystallizes to microcrystalline quartz, but banded opal-CT filling large pores recrystallizes to chalcedony.

As the supply of biogenic opal-A decreases, the siliceous pore water solutions become more dilute and megaquartz is precipitated as the last stage of chertification. This paragenetic sequence in chert fabrics identified by Meyers (1977) in Mississippian Lake Valley Formation cherts is identical to that of Redwall cherts: microcrystalline quartz followed by chalcedony and megaquartz.
CONCLUSIONS

1) Cherts of the Redwall Limestone in the Grand Canyon have been subdivided into six general classes based on field observations. Chert type I is composed of stratigraphically rare, irregular lenses of white chert in the lower Whitmore Wash Member. Chert type II contains oval nodules of white chert flattened in layers parallel to bedding in the upper Whitmore Wash Member. Chert type III comprises the white chert pseudobeds of the Thunder Springs Member. Chert type IV is composed of isolated, irregularly shaped nodules of incompletely chertified white chert in the middle of the Mooney Falls Member. Chert type V contains concentrically banded, dark gray chert lenses at the top of the Mooney Falls Member. Chert type VI comprises white pseudo-beded cherts with gray laminations occurring in the upper Horseshoe Mesa Member.

2) Chert type III, the bulk of Redwall cherts by volume, have been divided into four subtypes. Chert types IIIa, IIIb, and IIIc are intergradational and represent cherts in the lower, middle, and upper Thunder Springs Member, respectively. These cherts show increasing separation of chert and host dolomite upsection. Chert type IIIId is a chertified crinoidal biosparrudite which serves as a distinctive marker unit approximately 3.5 m (11.5 ft) below the top of the Thunder Springs Member.

3) Petrographic examination of all types of Redwall chert reveals that the cherts are composed of microcrystalline quartz,
chalcedony, megaquartz, dolomite, and calcite. Chert type I contains microcrystalline quartz, chalcedony, megaquartz, and dolomite. Chert type II is composed of microcrystalline quartz, megaquartz, and dolomite. Chert type III contains microcrystalline quartz, megaquartz, and euhedral dolomite rhombs. Chert type IV is composed of microcrystalline quartz and calcite. Chert types V and VI contain microcrystalline quartz, megaquartz, and concentrations of organic matter.

4) Redwall cherts have a consistent four-part diagenetic history of initial dolomitization, chertification, wholesale dolomitization, and dedolomitization. Chertification occurred in three stages: microcrystalline quartz replacement of lime mud and some fossils, chalcedonic void-filling cement, and megaquartz void-filling cement and replacement of fossils.

5) SEM micrographs show that Redwall cherts are composed of very fine-grained microcrystalline quartz. The equant grains range from 0.5 to 6 μm in diameter. In addition, two distinctive forms of silica have been recognized by SEM/EDXA studies. Possible chalcedony rods with calcite(?) crystallites occur within chert type I, and may be related to silica blades recently recovered by DSDP workers (Hein, Vallier, and Allan, 1981). Silica needles from chert type III are previously unknown.

6) Sponge spicules, identified in nearly all Redwall cherts, served as an indigenous source of biogenic silica. The spicules have been replaced by megaquartz following a moldic stage.

7) A mixing zone model for chertification (Knauth, 1979) is proposed for the Redwall Limestone based on stratigraphic relations of
various chert geometries, the association of chert and dolomite in chert type III, and the availability and petrography of siliceous sponge spicules. Stable isotope data from Knauth and Epstein (1976) offer independent evidence for a mixing zone model for chertification.

8) The chert paragenesis (microcrystalline quartz, chalcedony, megaquartz) found in Redwall cherts is similar to that observed by Meyers (1977) for Mississippian shallow shelf carbonates of New Mexico. Such a sequence records the increasingly dilute nature of pore waters as the supply of biogenic silica decreases.

9) Field description and detailed petrography are the foundations for studies of chertification which propose silica source, timing, and diagenetic environments for chert replacement of host carbonate rocks. Future studies of chertification will add to the body of knowledge about cherts, test present models, and contribute to a better understanding of the chertification process.

Recommendations for Further Studies

The results of this investigation suggest numerous avenues of research directed towards Redwall cherts in particular and chertification of limestones in general. Projects constraining geochemical parameters would add important information to this and all studies of chertification.

Stable isotope compositions of chert (oxygen, hydrogen) and dolomite (oxygen, carbon) could be used to infer diagenetic environments. Isotopic ratios of host dolomite and dolomite rhombs included in cherts may show evidence of having been precipitated in a marine/
meteoric mixing zone. Dilution by meteoric water favors the incorporation of the light 160 isotope into the solid dolomite phase (Land, Salem, and Morrow, 1975). Isotopic compositions of cherts from the Thunder Springs Member show a definite meteoric water component (Knauth, 1985, pers. comm.), but cherts from the Whitmore Wash, Mooney Falls, and Horseshoe Mesa Members have yet to be examined. A study of this scope would complement, and invite comparison with, the investigation of stable isotopes of chert and carbonate cements in the Mississippian Lake Valley Formation of New Mexico (Meyers and James, 1978).

Minor and trace element (Fe, Sr, Na, Mn) studies of host dolomite rhombs may also support a mixing zone model for dolomitization and chertification. Depletion in most trace elements towards the periphery of dolomite crystals is common in mixing zone dolomites (Morrow, 1982, p. 103). This trend reflects the progressively more dilute solutions which dissolve pre-existing calcite and precipitate dolomite.

Cathodoluminescence of cements in Redwall limestones and dolomites may yield a detailed cement stratigraphy and help to restrict the timing of chertification relative to carbonate cement generations. Characteristic cements have been correlated from sample to sample and can be related to a variety of tectonic and erosional events (Meyers, 1974).

Finally, an expanded SEM study of the unusual Redwall chert textures merits further consideration. Chalcedony(?) rods in Whitmore Wash cherts, apparently composed of silica and calcite, may be similar to silica blades recently reported by DSDP investigators (Hein,
Vallier, and Allan, 1981). Silica fibers found throughout the Thunder Springs cherts have not previously been described in the literature. An even distribution of chert samples from a wide geographic area may provide clues to the nature and origin of these distinctive crystal habits.
APPENDIX

MEASURED STRATIGRAPHIC SECTION

South Kaibab Trail

Section measured up South Kaibab Trail, Bright Angel Quadrangle, Grand Canyon National Park, Arizona. Horseshoe Mesa and Mooney Falls Members measured on south fault block, Thunder Springs Member measured on central fault block, and Whitmore Wash Member measured on north fault block.

Pennsylvanian:

Watahomigi Formation of the Supai Group:

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
<th>Unit Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Meters</td>
</tr>
<tr>
<td>6</td>
<td>Limestone (micrite); pale yellowish brown (10YR 6/2), weathers dark yellowish brown (10YR 4/2); contains large (30 cm) concentric rings of chert; thin-bedded, very thin beds (3 to 5 cm) at base; forms cliff with flat ledge on top</td>
<td>3.32</td>
</tr>
<tr>
<td>5</td>
<td>Covered</td>
<td>.65</td>
</tr>
<tr>
<td>4</td>
<td>Limestone (fossiliferous micrite); olive gray (5Y 4/1), weathers same; brachiopods and fossil hash; beds 10 to 30 cm; forms slope with few ledges</td>
<td>.91</td>
</tr>
<tr>
<td>3</td>
<td>Limestone (micrite); light olive gray (5Y 6/1), weathers same and moderate reddish brown (10R 4/6); beds 30 to 40 cm thick; forms receding ledges</td>
<td>1.08</td>
</tr>
<tr>
<td>2</td>
<td>Limestone (micrite); yellowish gray (5Y 8/1), weathers moderate reddish orange (10R 6/6); chert mottled dark gray (N3) and white (N9); massive; forms cliff</td>
<td>3.20</td>
</tr>
<tr>
<td>Unit No.</td>
<td>Description</td>
<td>Unit Thickness</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>----------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Meters</td>
</tr>
<tr>
<td>1</td>
<td>Limestone (micrite); very light gray (N8), weathers moderate reddish orange (10R 6/6); few chert lenses and nodules; massive; forms slope with few ledges</td>
<td>3.33</td>
</tr>
<tr>
<td></td>
<td>Total thickness basal Watahomig Formation</td>
<td>12.49</td>
</tr>
</tbody>
</table>

Unconformity

Mississippian:

Redwall Limestone:

Horseshoe Mesa Member:

26 Limestone (oomicrite); 80%; light olive gray (5Y 6/1), weathers moderate reddish orange (10R 6/6); very thin-bedded with one thicker bed (1 m) which is internally laminated; forms cliff; samples HM518-9 and HM518-10

and

Chert; 20%; white (N9), weathers moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); thin (2-5 cm) lenses; forms top of cliff

3.93 12.89

25 Limestone (oomicrite); 50%; light olive gray (5Y 6/1), weathers moderate reddish orange (10R 6/6); thin-bedded; forms part of cliff; sample 518-11

and

Chert; 50%; white (N9), weathers moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); thin pseudobeds; very continuous laterally; constant thickness; internally laminated; intensely fractured; forms cliff; sample HM518-8.

1.60 5.25

24 Limestone (packed oomicrite); light olive gray (5Y 6/1), weathers pale reddish brown (10R 5/4) to moderate reddish brown (10R 4/6); thin-bedded, with some thicker
Mooney Falls Member:

22 Limestone (packed oomicrite); light olive gray (5Y 6/1), weathers same, yellowish gray (5Y 7/2), weathers dark yellowish brown (10YR 4/2); massive; forms cliff; smooth, rounded weathered surface; basal 20 cm is incompletely silicified oomicrite in long rounded lenses; some ooids etched on weathered surface; upper 2 m contains thin pseudobeds of chert (description below), some with well-preserved brachio-pods and rugose corals; samples MF517-2, MF517-4, MF517-6, MF517-7

Chert; medium dark gray (N4), weathers dusky yellowish brown (10YR 2/2), light olive gray (5Y 6/1) to greenish gray (5GY 6/1), weathers dusky yellowish brown (10YR 2/2); thin pseudobeds (20-40 cm); intensely fractured; cherts concentrically banded, samples MF517-5, MF517-8, MF517-9, MF517-10 .................................. 34.72 113.89

21 Limestone (fossiliferous micrite); dusky yellow (5Y 6/4), weathers same or olive gray (5Y 3/2); has small (5 mm x 15 mm) calcite eyes in irregular shapes; thin-bedded; forms ledges, some with well-developed stylolites; samples MF517-1, MF517-3 .................................. 2.09 6.86

20 Limestone (packed oomicrite); pale yellowish brown (10YR 6/2), weathers dusky yellowish brown (10YR 2/2); massive; forms cliff; basal contact is irregular solution
<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
<th>Unit Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Limestone (fossiliferous micrite); pale yellowish brown (10YR 6/2), weathers dusky yellowish brown (10YR 2/2); massive; forms lower part of cliff; moderately to slightly weathered (chalky) in patches; chert nodules are mostly weathered out, leaving cavities; chert nodules occur in layers; contains bryozoans, crinoids, and occasional brachiopods; sample MF512-2</td>
<td>10.02 32.87</td>
</tr>
<tr>
<td>18</td>
<td>Limestone (fossiliferous micrite); white (N9) to very pale orange (10YR 8/2), weathers light brown (5YR 6/4); massive; smooth and rounded weathered surface; crinoids; forms slope; poorly exposed; porous; intensely weathered</td>
<td>1.82 5.97</td>
</tr>
<tr>
<td>17</td>
<td>Limestone (crinoidal biosparite); white (N9), weathers grayish orange pink (5YR 7/2); massive; weathers to a rounded but irregular surface; forms slope with few ledges</td>
<td>1.15 3.77</td>
</tr>
<tr>
<td>16</td>
<td>Limestone (biosparite); white (N9) to yellowish gray (5Y 7/2), weathers grayish orange pink (5YR 7/2); single bed; smooth weathered surface; slightly friable; forms slope</td>
<td>.76 2.49</td>
</tr>
<tr>
<td>15</td>
<td>Limestone (crinoidal biosparrudite); 80%; white (N9) to pinkish gray (5YR 8/1), weathers pale yellowish brown (10 YR 6/2) to dusky yellowish brown (10YR 2/2); massive; forms slope and ledges; poorly exposed</td>
<td></td>
</tr>
</tbody>
</table>

**Interfingering with**

Dolomite (finely crystalline calcareous dolomite); 20%; pale yellowish brown (10YR 6/2) to grayish orange (10YR 7/4), weathers dark yellowish brown (10YR 4/2); massive; forms slope and ledges; poorly exposed | 4.63 15.19
<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
<th>Unit Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Mooney Falls Member</strong></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Limestone (crinoidal biosparrudite); 50%; white (N9) to pinkish gray (5YR 8/1), weathers olive gray (5Y 4/1); thick-bedded to massive; forms slope and ledges <strong>interfingering with</strong> Dolomite (finely crystalline calcareous dolomite); 50%; very pale orange (10YR 8/2) to pale yellowish brown (10YR 6/2), weathers dusky yellowish brown (10YR 2/2); thick-bedded to massive; forms slope and ledges; poorly exposed ........................................ 2.19 7.18</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Limestone (biosparite); white (N9) to pinkish gray (5YR 8/1), weathers grayish orange (10YR 7/4); forms slope; single bed; contains fossil hash; moderately weathered; slightly friable; poorly exposed; smooth weathered surface ........................................... .18 .59</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Limestone (crinoidal biosparrudite); white (N9) to pinkish gray (5YR 8/1), weathers to light olive gray (5Y 6/1) to medium gray (N5); thin- to thick-bedded; forms ledges and slopes (on N and S fault blocks) and cliff (on middle fault block); rugose corals, crinoids; rare cross-laminations (on middle fault block just W of TS-MF contact along trail); sample MF512-1 ........................................... 3.88 12.73</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Limestone (fossiliferous micrite); very pale orange (10YR 8/2), weathers yellowish gray (5Y 7/2); massive; forms slope; partly covered; some patches of crinoid ossicles; smooth, rounded weathered surface; well-developed stylolites ............................................. .86 2.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total thickness Mooney Falls Member</strong> ................................ 74.50 244.37</td>
<td></td>
</tr>
</tbody>
</table>

**Thunder Springs Member:**

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
<th>Unit Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Limestone (slightly dolomitic sparse biomicrite); grayish orange pink (5YR 7/2), weathers light brown (5YR 6/4) and moderate reddish brown (10R 4/6); crinoid ossicles; massive; porous; forms top of cliff with</td>
<td></td>
</tr>
</tbody>
</table>
Unit No. | Description | Unit Thickness
--- | --- | ---
9 | *irregular ledge at top; samples TS510-25, TS510-26* | 2.50 8.20

Dolomite (finely crystalline dolomite); 65%; pale red (5R 6/2) mottled with yellowish gray (5Y 7/2), weathers moderate reddish brown (10R 4/6) and moderate brown (5YR 4/4); very thin-bedded; bryozoans, brachiopods, crinoids; moldic porosity; forms part of cliff; possible Planolites

and

Chert; 35%; white (N9) to yellowish gray (5Y8/1) and light olive gray (5Y 6/1), weathers light olive gray (5Y 6/1), moderate orange pink (5Y 8/4), and grayish orange (10YR 7/4) to dusky yellowish brown (10YR 2/2); thin (1 cm) to thick (10 cm) pseudobeds, very irregular but continuous; very indurated; bryozoans, brachiopods, and crinoids; forms part of cliff; samples TS510-23, TS510-24

8 | *Limestone (crinoidal biosparrudite)*; pinkish gray (5YR 8/1), weathers light brown (5YR 6/4); single bed, varies from 22 to 28 cm; sample TS510-23a | .75 2.46

7 | *Dolomite (dolomitic sparse biomicrite)*; 75%; pale red (5R 6/2), weathers to pale red brown (10R 5/4), gradually changing upsection to mottled pale red (5R 6/2) and pale yellowish brown (10YR 6/2), and becoming olive gray (5Y 4/1) near the top; dolomite content decreases near the top to only slightly dolomitic; thin-bedded; some moldic porosity; forms resistant cliff, ledges in some places

and

Chert; 25%; pinkish gray (5YR 8/1) to white (N9) to yellowish gray (5Y 8/1), weathers light brown (5YR 5/6) and light olive gray (5YR 6/1) to dusky yellowish brown (10YR 2/2); molds of bryozoans, crinoids,
<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
<th>Unit Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Meters</td>
</tr>
<tr>
<td>6</td>
<td>Dolomite (dolomitic sparse biomicrite); 50%; pale red (5R 6/2), grayish orange pink (5YR 7/2), and moderate red (5R 5/4), weathers light brown (5YR 6/4) to light brown (5YR 5/6); thin-bedded; forms very resistant cliff; top of unit is flat ledge and Chert; 50%; white (N9), weathers moderate reddish orange (10R 6/6) to moderate reddish brown (10R 4/6); bryozoans, brachiopods; very thin-bedded; friable, becoming more indurated towards top; samples TS510-6 to TS510-20</td>
<td>2.28</td>
</tr>
<tr>
<td>5</td>
<td>Limestone (dolomitic, finely crystalline, fossiliferous micrite); 75%; medium light gray (N6) to light brownish gray (5YR 6/1), weathers dark yellow brown (10YR 4/2); thin-bedded; forms cliff, some ledges; <em>Planolites</em> (?); calcite vugs and Chert; 25%; pinkish gray (5YR 8/1), weathers light brown (5YR 5/6) to moderate brown (5YR 4/4) and dusky yellowish brown (10YR 2/2); discontinuous pseudobeds of variable thickness (1 to 15 cm); forms cliff, some ledges; samples TS510-1 to TS510-5</td>
<td>15.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total Thickness Thunder Springs Member</td>
<td>26.50</td>
</tr>
</tbody>
</table>

**Whitmore Wash Member:**

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Dolomite (medium crystalline calcitic dolomite); light brownish gray (5YR 6/1), weathers moderate yellowish brown (10YR 5/4); very thick-bedded; forms cliff; abundant moldic porosity; contains oval chert nodules (15 cm x 30 cm)</td>
</tr>
<tr>
<td>Unit No.</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Dolomite (fine to medium crystalline dolomite); light gray (N7) and grayish orange (10YR 7/4), weathers same and dark reddish brown (10YR 4/2) to dusky reddish brown (10YR 2/2); laminated; occasional frosted quartz grains; single bed; contains small cubes of limonite after pyrite; forms base of cliff; sample WW512-1, WW512-2 ....................................................................................................................</td>
</tr>
<tr>
<td>2</td>
<td>Dolomite (finely crystalline calcite dolomite), medium dark gray (N5) to medium gray (N6), weathers pale yellowish brown (10YR 6/2), pale yellowish brown (10YR 6/2), weathers same to dark yellowish brown (10YR 4/2); parallel laminations and cross-laminations; thin-bedded; brachiopods and crinoids form moldic porosity; forms cliff; top of unit is narrow ledge; contains rare elongate lenses of chert ........................................................................................................................................</td>
</tr>
<tr>
<td>3</td>
<td>Dolomite (coarsely crystalline calcite dolomite); pale red (10R 6/2), weathers pale brown (5YR 5/2); massive; cliff former; occasional fossil molds ........................................................................................................................................................................................................................................................................................................................................</td>
</tr>
<tr>
<td></td>
<td>flattened parallel to bedding, with an average distance apart of 30 to 40 cm; small crinoid ossicles and bryozoan fronds well-preserved in cherts; samples WW510-1, WW510-2; WW510-3 ........................................................................................................................................................................................................................................................................................................................................</td>
</tr>
<tr>
<td></td>
<td>Total thickness Whitmore Wash Member ........................................................................................................................................................................................................................................................................................................................................</td>
</tr>
<tr>
<td></td>
<td>Unconformity assumed</td>
</tr>
<tr>
<td></td>
<td>Covered interval ........................................................................................................................................................................................................................................................................................................................................................................................................</td>
</tr>
<tr>
<td></td>
<td>Devonian:</td>
</tr>
<tr>
<td></td>
<td>Temple Butte Formation:</td>
</tr>
<tr>
<td>11</td>
<td>Dolomite (fine to medium crystalline dolomite); pale red (10R 6/1) to light brownish gray (5YR 6/1), weathers grayish orange pink (5YR 7/2); very thin to thin-bedded; forms slope; poor exposure ........................................................................................................................................................................................................................................................................................................................................</td>
</tr>
<tr>
<td>Unit No.</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>10</td>
<td>Dolomite (very coarsely crystalline dolomite); grayish orange pink (5YR 7/2), weathers light brown (5YR 6/4) to moderate orange pink (5YR 8/4); basal 15 cm is laminated, calcareous, finely crystalline; massive; forms cliff.</td>
</tr>
<tr>
<td>9</td>
<td>Covered</td>
</tr>
<tr>
<td>8</td>
<td>Dolomite (finely crystalline dolomite); medium gray (N5), weathers light brown (5YR 6/4); sandy; thin-bedded; forms cliff.</td>
</tr>
<tr>
<td>7</td>
<td>Dolomite (finely crystalline dolomite); medium gray (N5), weathers olive gray (5Y 4/1); thin-bedded; pore spaces lined with large dolomite rhombs; forms ledges; poorly exposed.</td>
</tr>
<tr>
<td>6</td>
<td>Sandstone (quartzarenite); pinkish gray (5YR 8/1), weathers moderate orange pink (5YR 8/4); medium-grained; carbonate cement; internally laminated; very thin-bedded; extremely porous; very friable; forms slope.</td>
</tr>
<tr>
<td>5</td>
<td>Dolomite (finely crystalline dolomite); medium gray (N5), weathers light brown (5YR 6/4); thin-bedded; pore spaces are partially filled with large dolomite rhombs; forms ledges.</td>
</tr>
<tr>
<td>4</td>
<td>Dolomite (coarsely crystalline dolomite); light olive gray (5Y 6/1), weathers light brown (5YR 6/4); faintly laminated; thick-bedded; forms top of cliff.</td>
</tr>
<tr>
<td>3</td>
<td>Sandstone (quartzarenite); grayish pink (5R 8/2), weathers moderate orange pink (5YR 8/4); medium-grained; carbonate cement; internally laminated; very thin-bedded; basal contact is sharp and undulatory; extremely porous; very friable; forms weak cliff.</td>
</tr>
<tr>
<td>Unit No.</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2</td>
<td>Dolomite (finely crystalline dolomite); medium gray (N5), weathers light olive gray (5Y 6/1); single bed; forms part of cliff</td>
</tr>
<tr>
<td></td>
<td>Total thickness of measured Temple Butte Formation</td>
</tr>
<tr>
<td>1</td>
<td>Dolomite (coarsely crystalline dolomite); grayish blue (5PB 5/2)</td>
</tr>
</tbody>
</table>
REFERENCES CITED


Knauth, L.P., 1985, Personal communication, March 26: Professor of Geochemistry and Head of Geology Department, Arizona State Univ., Tempe, Arizona.


