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CONTENTS

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Cover: Moenkopi Formation, Southern Utah

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Stratigraphy and Facies Analysis of the Upper Kaibab and Lower Moenkopi Formations in Southwest Washington County, Utah*

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ABSTRACT

Pre-Moenkopi karst topography formed on the nonresistant gypsum beds of the Permian Harrisburg Member of the Kaibab Formation in the Beaver Dam Mountains of southwestern Utah. Local relief on the erosional surface may be more than 180 m, forming potential unconformity traps with substantial closure.

Upper Permian and Lower Triassic rocks in the Beaver Dam Mountains accumulated on a gently westward-sloping continental shelf as both carbonate and clastic tidal flat environments. Facies analyses show seven lithofacies including mudstone, siltstone, dolomite, silty wackestone, fossiliferous packstone, and pelloidal-ooidal grainstone to packstone. Gypsum and dolomite facies formed mainly on supratidal flats. Packstone and grainstone rocks formed mainly on shoals, bars, and banks in the intertidal zone of a carbonate tidal flat. Mudstone and siltstone units formed mainly on muddy tidal flats.

High-displacement basin-and-range normal faults have uplifted the rocks, forming good exposures of the Permian and Triassic strata in the Beaver Dam Mountains and perhaps forming structural traps to the east. Stratigraphic traps may also occur throughout the Permian Harrisburg and Triassic Shnabkaib Members. Thick anhydrite beds form the cap rock. Grainstone, packstone, and dolomite units may be effective reservoir rocks. Source rocks include algal-rich wackestone and dolomite beds, fossiliferous units, including the underlying Fossil Mountain Member, and organic-rich mudstone units. Even though trapping mechanisms are abundant in the Beaver Dam Mountains, oil exploration has not been very successful to date, but this may be due, in part, to the difficulty of locating suitable traps.

INTRODUCTION

Karst topography with local relief of more than 180 m and large collapse structures characterize the contact between the Permian and Triassic strata in the Beaver Dam Mountains of southwestern Utah. Because the Moenkopi Formation was deposited on an uneven surface, its lower members range greatly in thickness and the lowest members are present only where they filled valleys on the Harrisburg surface. The Harrisburg Member and the Moenkopi Formation were deposited in shallow marine through clastic tidal flat environments on the cratonic platform that fringed western North America. High-displacement basin-and-range normal faults have uplifted the rocks, forming good exposures of the Permian and Triassic strata in the Beaver Dam Mountains.

The purpose of this study is (1) to document the stratigraphy of the Upper Permian and Lower Triassic strata of the Beaver Dam Mountains, (2) to describe the nature of the unconformity between the Permian and Triassic rocks, and (3) to make a facies analysis and determine the depositional environments for these rocks.

LOCATION

The study area, shown in figure 1, is located on the east flank of the Beaver Dam Mountains in Washington County, Utah, and is readily accessible via Utah 91 and graded dirt roads, the principal ones being the Utah 91 Loop Road (91LR on all diagrams), the road to Motoqua, and the road that connects Bloomington to Utah 91.

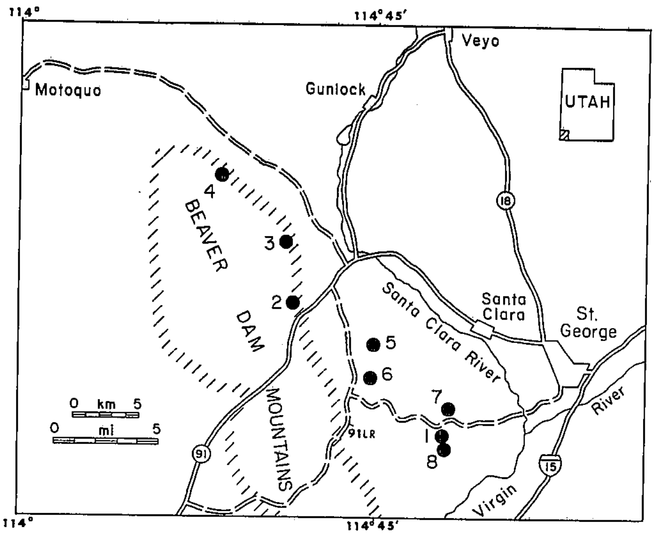
*A thesis submitted to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science, January 1984.

FIELD METHODS

Measurement and description of the sections were carried out during the spring, summer, and fall of 1983. Handsamples were collected at every significant lithologic change, and special care was taken to sample unweathered rocks. The Geological Society of America rock color chart was used to determine the colors of the rocks.

LABORATORY METHODS

More than 130 thin sections were prepared and examined for microsedimentary structures and fossils. Half of each thin section was stained with Alizarin Red S (Sabins 1962) to help determine the relative amounts of calcite and dolomite. Selected slides were also stained with potassium ferrocyanide solution (Lindholm and Finkleman 1972). Several samples from each limestone ledge in the Virgin Limestone Member and many samples from the dolomite ledges in the other members were dissolved in dilute reagent acetic acid. The residue was then washed on a 120-mesh screen, dried, and thoroughly examined under a binocular microscope, checking for conodonts, but none were found.



Section 1 N½, NE½, Section 24, T43S, R17W
Section 2 NW¼, SE½, Section 1, T42S, R18W*
Section 3 S½, N½, Section 25, T41S, R18W
Section 4 NE¼, SW¼, Section 31, T40S, R18W*
Section 5 NW¼, NW¼, Section 10, T42S, R17W*
Section 6 SE¼, NW¼, Section 33, T42S, R17W*
Section 7 NE¼, NW¼, Section 18, T43S, R16W
Section 8 SE¼, NE¼, Section 24, T43S, R17W

*Location given at the base of the measured section.

FIGURE 1.—*Locations of the measured sections.*

Representative samples (averaging 280 grams apiece) from each of the ledges of the Virgin Limestone Member and from several dolomite ledges were analyzed for insoluble residue content. Each sample was weighed and dissolved in dilute HCl. Insoluble residues remaining, after washing through filter paper, were dried, weighed, and examined for clastic mineralogy. Fossils collected from the Virgin Limestone Member were sent to the Smithsonian Institution for identification and dating by John Pojeta, Jr., and Renjie Zhang.

TERMINOLOGY

Carbonate nomenclature used in this study follows the scheme of Dunham (1962), who classified rocks on the basis of their depositional texture. Terminology and recognition criteria for diagenetic textures follows Bathurst (1975).

PREVIOUS WORK

Historical development of the Upper Permian and Lower Triassic nomenclature used in the Beaver Dam Mountains is shown in figure 2. The first comprehensive regional study of the stratigraphy, facies, and depositional environments of the Moenkopi Formation was done by McKee (1954). Sorauf (1962) proposed formal names for the members of McKee (1938), but he did not publish his suggested names and they did not appear in a formal publication until used by Nielson and Johnson (1979). Stewart and others (1972) did a second regional study of the Moenkopi Formation, which included lithologic and faunal descriptions and an attempt to correlate the numerous locally recognized units.

Several recent theses and dissertations have been completed on the Kaibab and Moenkopi Formations: Olmore (1971) studied the Virgin Limestone Member, attempting to determine the evolution of thrust faults in the Mormon Mountains of Nevada. Blakey (1974) analyzed the Moenkopi Formation in southeastern Utah. Clark (1974) did a facies analysis of the Harrisburg Member in Whitmore Wash. Skyllingstad (1977) studied the depositional environment and diagenetic history of the Virgin Limestone Member. Reif (1978) examined the depositional environments of the red beds of the Moenkopi Formation. Nielson (1982) analyzed the depositional environments of the Kaibab and Toroweap Formations. Shorb (1983) studied the stratigraphy, facies, and depositional environments of the Moenkopi Formation on a regional scale with most of his work being done in eastern Nevada, and Marlay (1983) analyzed the diagenesis of the lower Moenkopi Formation. For a more comprehensive history of previous work see Nielson (1982).

GEOLOGIC SETTING

The depositional history of southwestern Utah during Late Permian and Early Triassic time was dominated by three principal paleotectonic elements (figs. 3 and 4). To the west was the Cordilleran miogeosyncline, a major subsiding trough that extended from present-day Montana to Baja California. This trough had been the locus of marine sedimentation from late Precambrian through Early Triassic times (Dean 1981). McKee and others (1967) stated that the outline of the Cordilleran miogeosyncline in the Permian is clearly defined by the 3000- and 4000-ft isopachs (915–1220 m), and that sediments attain a thickness of more than 7000 ft (2134 m) in its central part. Bissell (1969) estimated that more than 1500 m of sediment were deposited in this trough in the Early Triassic. Irwin (1971) stated sedimentation in southwestern Utah was influenced by three principal depositional areas: "the Oquirrh basin in north-central Utah, the Cordilleran miogeosyncline in eastern Nevada and the Quemado-Cuchillo basin in east-central Arizona." Each basin seems to have received sediments during a discrete period of geologic time. Thus, while one basin was receiving sediments, others were not (Irwin 1971).

To the east the Defiance Uplift, San Juan Uplift, and Uncompahgre Highland continued to supply clastic sediments during the deposition of the Moenkopi Formation as they had since Middle Pennsylvanian time (McKee and others 1967). Blakey (1974) considered the Uncompahgre Highland and the Mogollon Highland as the main contributors of clastic sediments to the Moenkopi Formation. These source areas had been producing sediments since the Pennsylvanian (McKee and others 1967) and waned toward the Late Triassic, as indicated by the burial of the Uncompahgre rocks by the Chinle Formation (McKee and others 1967).

The third element was a broad, gentle westward-sloping shelf, onto which most of the Moenkopi sediments were deposited (McKee and others 1967). Sediments were deposited on the platform in very shallow water environments, probably never exceeding 10 m in depth (Shorb 1983). The limestone members were deposited during transgressions of the seas, and the clastic red beds during regressions.

Gregory (1917)	Reeside & Bassler (1922)	McKee (1938)	Gregory (1950)	Poborski (1954)	Sorauf (1962)
Moenkopi	Moenkopi Formation: upper red		Moenkopi Formation: upper red	Moenkopi Formation: upper red	
	Shnabkaib		Shnabkaib	Shnabkaib	
	middle red		middle red	middle red	
	Virgin Limestone		Virgin Limestone	Virgin Limestone	
	lower red		lower red	lower red	
	Rock Canyon Conglomerate		Timpoweap	Timpoweap	
	Aubrey Group: Kaibab Limestone: Harrisburg Gypsiferous	Aubrey Group: Kaibab Fm.: α			Aubrey Group: Kaibab Fm.: Harrisburg
	limestone	β			Fossil Mt.
	soft beds	γ			not present
	limestone	Toroweap Fm.: α			Toroweap Fm.: Woods Ranch
	gypsum	β			Brady Canyon
	Coconino Sandstone	γ			Seligman

FIGURE 2.—*Table showing the historical development of the nomenclature for the Upper Permian and Lower Triassic formations in southwestern Utah and northern Arizona.*

STRATIGRAPHY

INTRODUCTION

The Leonardian Kaibab Formation is a deposit of the greatest marine transgression of Permian time (Cheevers and Rawson 1979). In southwestern Utah shallow marine conditions existed during deposition of the Fossil Mountain Member (Mckee and others 1967). This was followed by a regression, forming lagoonal evaporitic deposits of the Harrisburg Member as shown in figure 5 (Mckee and others 1967). Guadalupian and Ochoan age deposits are missing from this area (Baars and others 1979).

Regionally the Kaibab Formation overlies the Permian Toroweap Formation and underlies the Triassic Moenkopi Formation. Both the lower and upper contacts of the Kaibab are erosional unconformities.

The Moenkopi Formation is a wedge-shaped deposit that thickens to the north and west (Blakey 1974) and attains thicknesses of over 760 m in southeastern Nevada (Bissell 1969). The depositional environments of the Moenkopi range from continental to shallow marine shelf environments. Most of the Moenkopi sediments were thought to have been deposited on a westward-dipping shelf, 640 km long and 160 to 480 km wide (Blakey 1974).

Regionally the Moenkopi Formation overlies the Permian Kaibab Formation and underlies the Upper Triassic Chinle Formation. Both the lower and upper contacts of the Moenkopi Formation are erosional unconformities. Measured stratigraphic sections of this study are shown in figure 6.

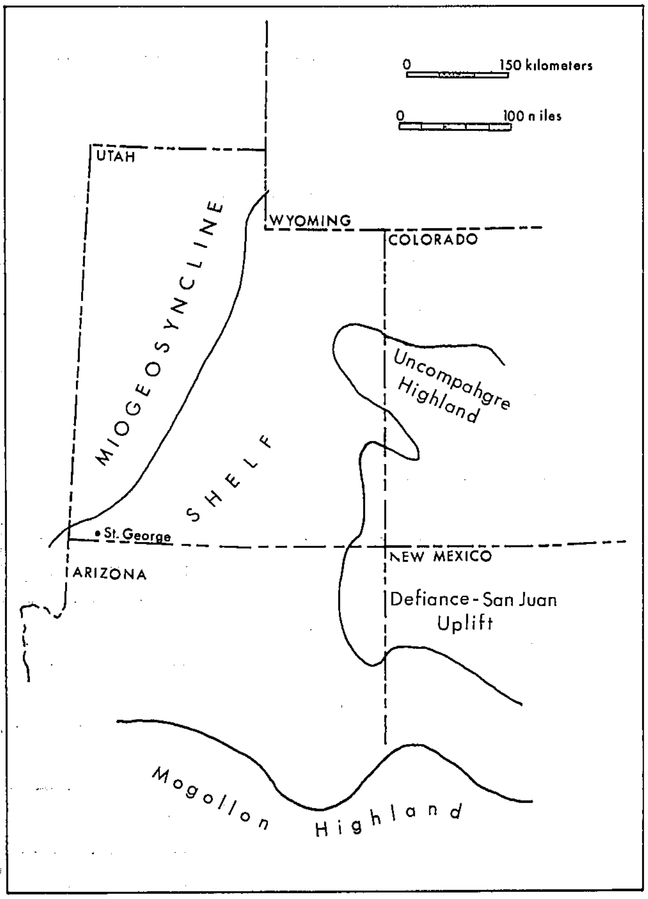


FIGURE 3.—*Map showing location of paleotectonic elements during Late Permian and Early Triassic time (modified after Blakey 1974).*

PERMIAN KAIBAB FORMATION

Fossil Mountain Member

The Fossil Mountain Member of the Kaibab Formation forms cliffs throughout the Beaver Dam Mountains. It is composed predominantly of light to medium gray limestone and contains abundant disseminated chert in the upper part and numerous fossils, especially *Pentacrinus* columnals and bivalves. This member stands in stark contrast to the overlying nonresistant Harrisburg Member, and is easily identified. Measured stratigraphic sections in this study begin at the top of the Fossil Mountain Member and go up. The average thickness of this member is approximately 90 m (Nielson 1982).

Harrisburg Member

The Harrisburg Member in the Beaver Dam Mountains is predominantly gypsum (85%). The rest of the section is composed of thin beds of dolomitic siltstone and dolomite, with the latter containing varying amounts of chert. Coarse dissolution collapse breccias were observed

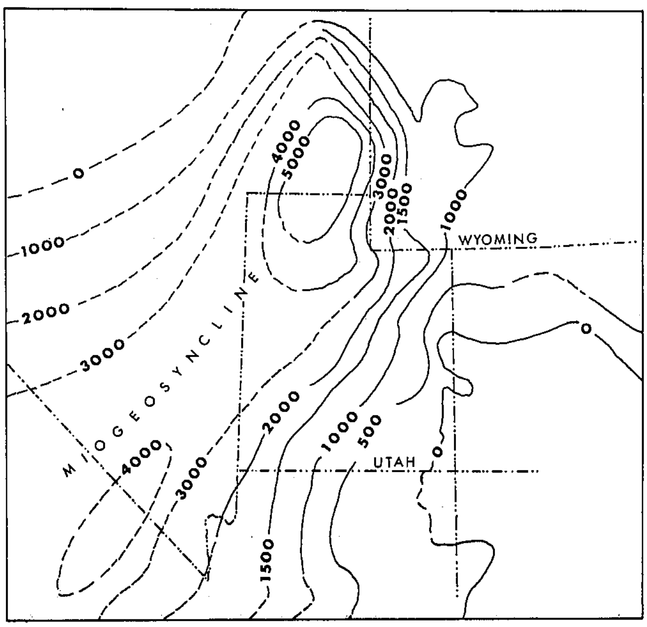


FIGURE 4.—*Isopach map showing the thickness of Triassic strata at the end of Triassic time (after McKee and others 1959).*

in several locations (fig. 7). These collapsed structures may have more than 20 m of relief. The Harrisburg Member in the Beaver Dam Mountains can be divided into three distinct units: (1) a lower unit composed almost entirely of gypsum (90%), (2) a middle dolomitic siltstone and dolomite unit formed of 2- to 3-m ledges of cherty dolomite alternating with 3- to 10-m slopes of gypsum, (3) an upper gypsum unit similar to the lower one.

In the lower unit the gypsum shows a nodular pattern in outcrop, but where it can be seen in cross section it is laminated (fig. 8). The gypsum is a light to medium gray and weathers to form a powdery, puffy, very resistant mass that covers most of the thin units that are interbedded with it. In several places throughout the Beaver Dam Mountains bulldozers have removed the upper gypsum covering to determine if the gypsum is economical, but just a meter or two below the surface the gypsum is anhydrite. The gypsum forms slopes that range from approximately 7 degrees up to as much as 27 degrees without appearing in outcrop to have any change in lithology. The quantity of thin beds and lenses of dolomite, and dolomitic siltstone determine the steepness of the gypsum slopes.

The dolomite beds are very light gray to light gray, thin bedded, and finely crystalline. Usually the beds are only a few cm thick, but may form ledges 1 to 2 m thick. They normally contain echinoderm (*Pentacrinus*) fragments, bivalve and bryozoan fragments, silt grains, and chert.

The siltstone beds are reddish brown and are composed predominantly of fine-grained quartz. The quartz grains are subangular to subrounded with poor sphericity. Some siltstone beds show trace fossils and others have ripple marks and small-scale cross-bedding. This unit constitutes the lower 100 m of the member.

The middle unit of the Harrisburg Member is composed of approximately 70% gypsum, which forms slopes, and 30% cherty dolomite and/or dolomitic siltstone, which forms ledges. The gypsum in this unit is similar to the gypsum in unit one. The dolomite and dolomitic siltstone beds are 1 to 2 m thick, have thick to massive bedding and a blocky splitting. They are usually light to medium gray. The dolomite ledges contain chert nodules at their bases. Chert becomes more abundant toward the top, forming disseminated chert, which constitutes at least 40% of the ledge surface. The chert is medium gray on a fresh surface, but weathers to a reddish or rust color. This red chert forms an easily identifiable horizon throughout much of the Beaver Dam Mountains. Other lithologic characteristics of the dolomite layers are similar to the lowest unit. This unit is 20 m thick.

The upper unit of the Harrisburg Member is similar to the lower unit except that it contains slightly more silt interspersed within the gypsum. The most fossiliferous bed in the member occurs in the middle of this unit. This bed crops out 151 meters above the base in section 1 and is 4 to 10 cm thick. It is a dark gray dolomite containing abundant shell fragments of bivalves with some crinoids and fine quartz silt. The upper unit is 58 m thick.

The lower contact of the Harrisburg Member is gradational with the underlying Fossil Mountain Member, whereas the upper contact is an erosional unconformity. In some areas the lower red member of the Moenkopi

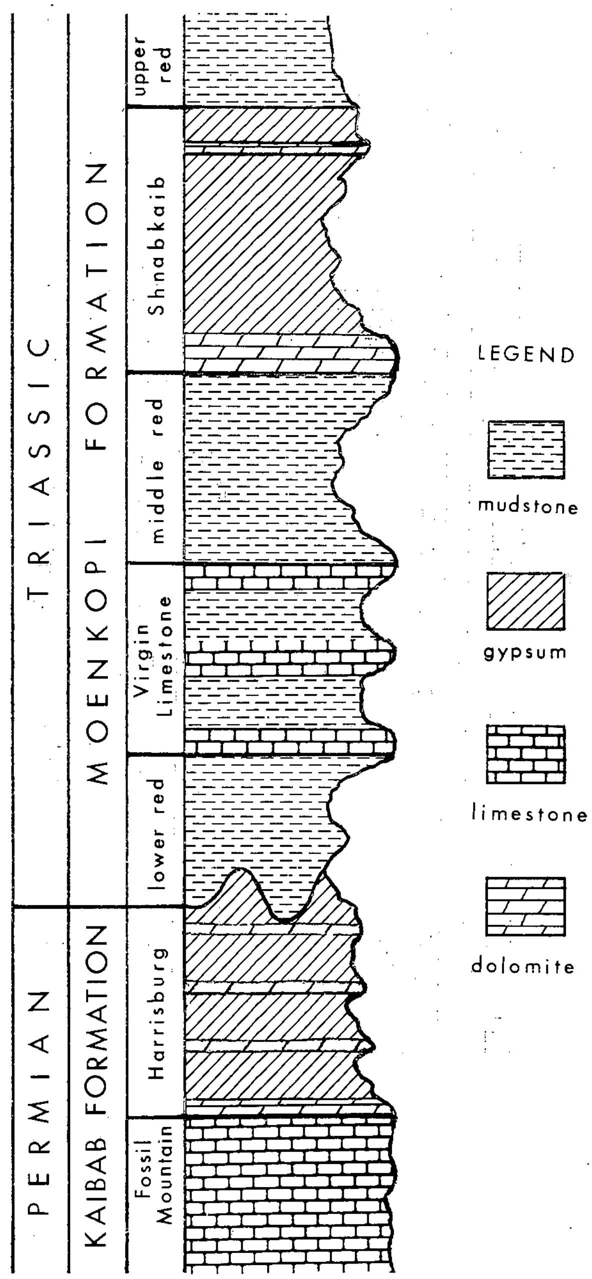


FIGURE 5.—*Schematic stratigraphic section showing the members present in the Beaver Dam Mountains. Thicknesses are not shown to scale.*

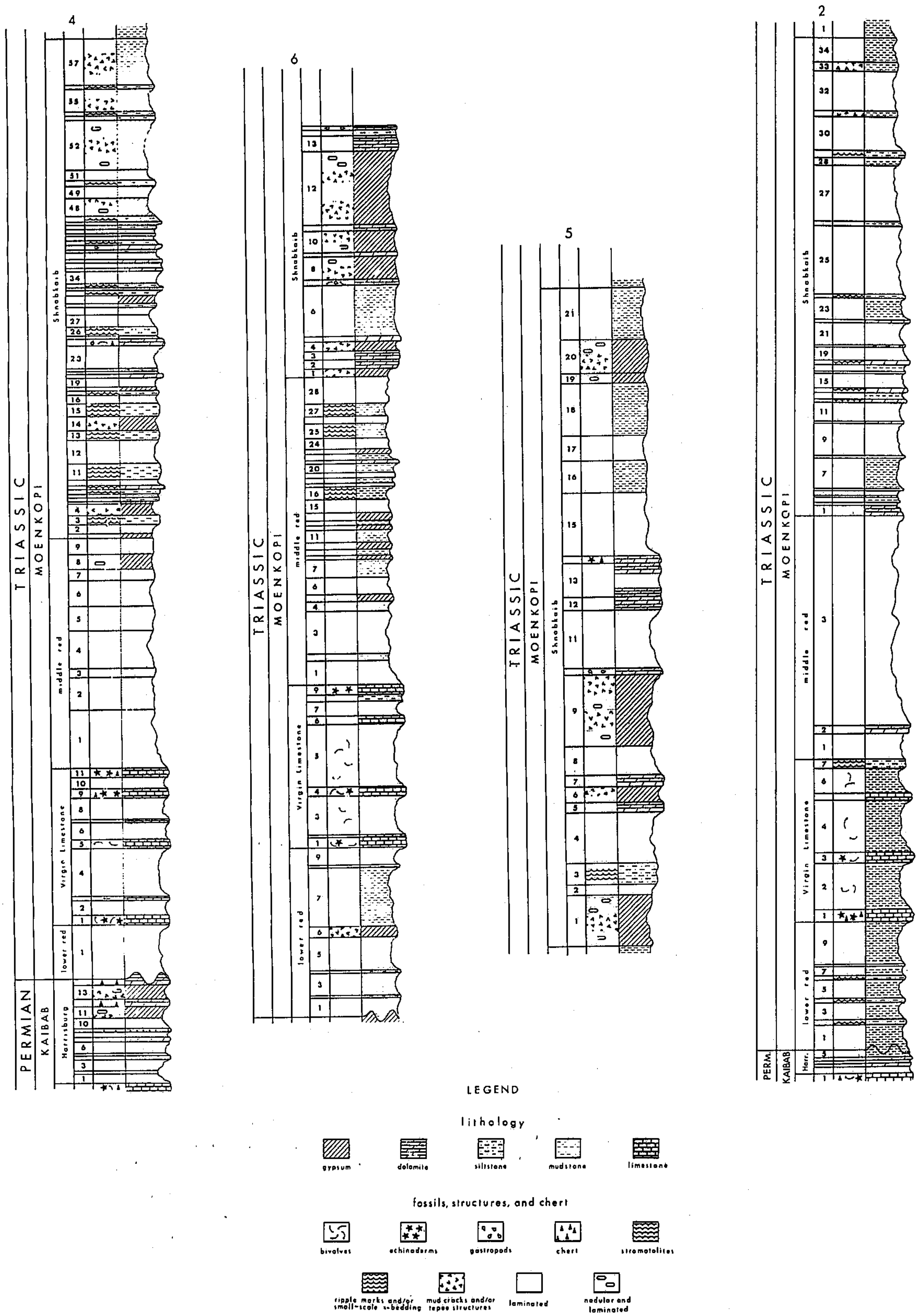
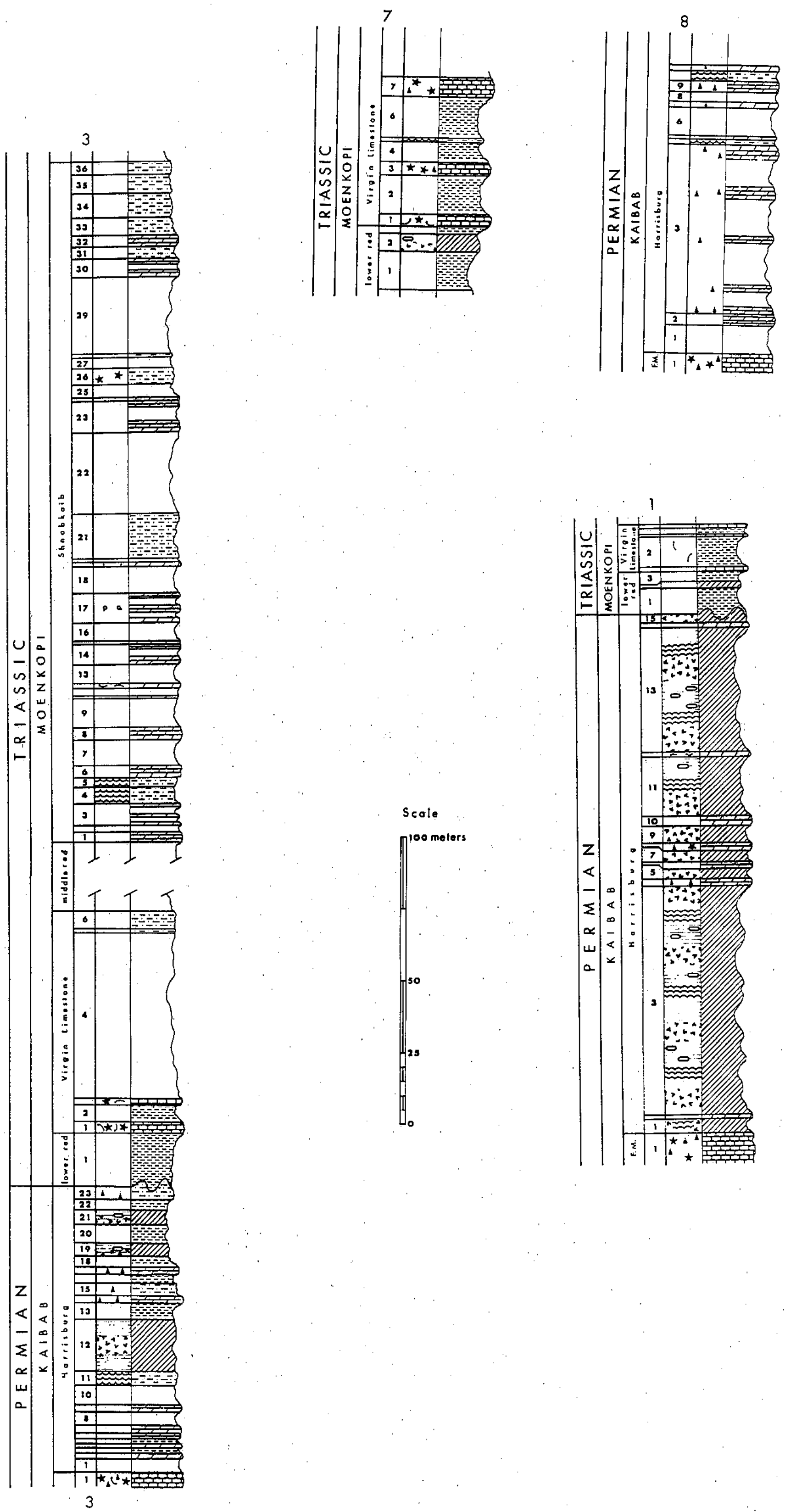


FIGURE 6.—*Measured stratigraphic sections.*


3
7
8
1
TRIASSIC
MOENKOPI
PERMIAN
KAIBAB
Harrisburg
Shnabkaib
middle red
Virgin Limestone
lower red
F.M.
Scale
100 meters
50
25
0

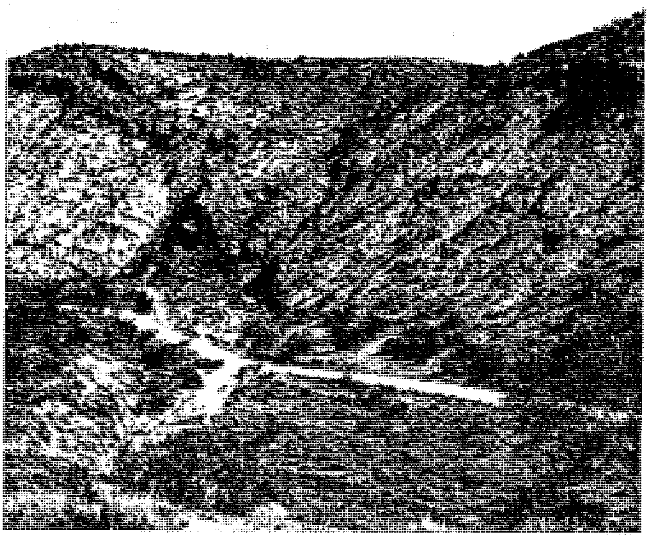


FIGURE 7.—*Collapse structures like the one in the center of the photograph are common in the Beaver Dam Mountains. Here the underlying gypsum was removed by solution activity and the resistant dolomite units on top collapsed forming a breccia. The road is approximately 6 m wide. This collapse structure is located approximately 100 m north of section 1.*

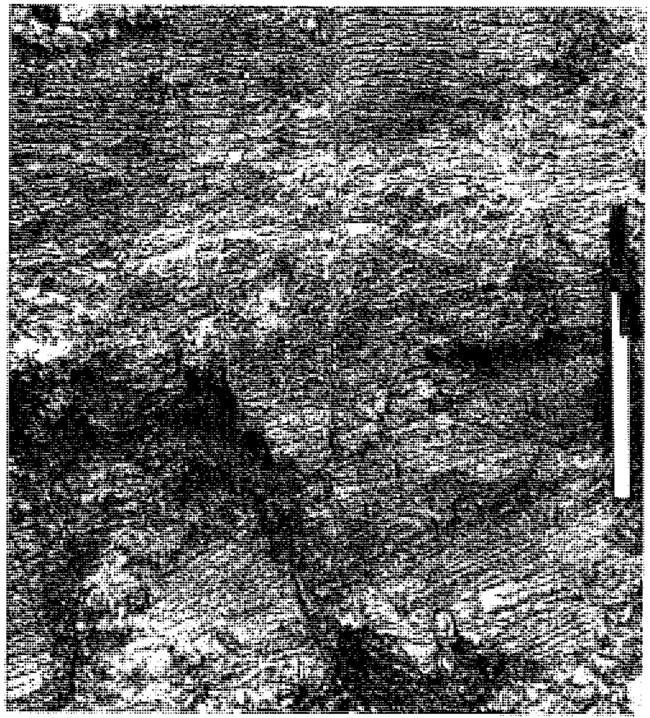


FIGURE 8.—*Laminated gypsum shown in the upper portion of the photograph with some cross-bedded gypsum in the lower portion. Photograph from the lower red member, section 6, approximately 38 m above the base.*

Formation overlies the Harrisburg Member, and in other areas the Virgin Limestone Member of the Moenkopi overlies the Harrisburg Member. Thicknesses of the Harrisburg Member range from 10 to 181.4 m.

UNCONFORMITY BETWEEN THE PERMIAN AND TRIASSIC STRATA

In pre-Moenkopi time karst topography developed on the Harrisburg strata. The nonresistant gypsum beds were completely eroded away in some areas, leaving collapse breccias or perhaps even valleys eroded into the Fossil Mountain Member. The original thickness of the Harrisburg Member at the time of deposition may have been more than the thickest section preserved. Approximately 1 km north of section 6, the Virgin Limestone Member directly overlies the Harrisburg Member with a paleosoil horizon between them. The Virgin Limestone Member's lowest limestone ledge thins and disappears here, indicating that a paleohill of Harrisburg strata must have been above the Virgin sea level. Paleohills of Harrisburg strata probably formed many small islands in the Virgin Sea, but they were all eventually buried by beds of the Virgin Limestone Member.

The lower red member in the Beaver Dam Mountains ranges in thickness from 0 to 67.7 m. Where it thickens the Harrisburg Member thins and vice versa. The Virgin Limestone Member thins approximately 3–5 m or more where paleohills of Harrisburg strata occur. This indicates that relief on the Harrisburg strata must have been at least 70 m. The Harrisburg Member ranges more than 171 m in thickness, but much of this may be due to later dissolution of the gypsum.

TRIASSIC MOENKOPI FORMATION

Nielson (1982) stated that no Timpoweap was deposited around the topographic remnants of the Kaibab Formation west of the Beaver Dam Mountains and that the Timpoweap Member is represented locally in the Beaver Dam Mountains only by minor amounts of yellowish orange siltstone and biomicrite. No strata of the Timpoweap Member were noted in any of the measured sections of this study.

Lower Red Member

The lower red member of the Moenkopi Formation is a nonresistant, slope-forming unit, composed predominantly of reddish brown siltstone and mudstone. The siltstone and mudstone are calcareous or dolomitic and thin beds of gypsum and carbonates crop out throughout the member. This member can be divided into three units: a lower unit composed of reddish brown siltstone and mudstone units, a middle unit composed predominantly of gypsum (80%), and an upper unit similar to the lower unit but containing more silt and less gypsum.

The lower unit of the lower red member consists mostly of horizontally laminated or structureless mudstone and siltstone that generally exhibits small-scale cross-bedding, lenticular bedding, flaser bedding, and bimodal ripple laminations. Ripple marks were observed on many of the siltstone units, having a bimodal paleo-current direction of northwest–southeast (fig. 9). Near the bottom of the unit the siltstone and mudstone beds contain abundant yellowish brown intraclasts of calcareous mud, up to 1 cm in diameter. Gypsum is common as secondary stringers of coarse satin spar and horizontal laminae, making up about 10% of the unit. This unit forms a gentle slope and is usually about 35 m thick.

The middle unit is composed mainly of gypsum (80%), which is a light olive gray in outcrop, horizontally laminated, and forms ledges. In places the gypsum is cross-bedded and formed of detrital gypsum grains (see fig. 8). Interbedded with the gypsum are thin beds of siltstone and mudstone similar to those in the lower unit, except for certain light tan, small-scale cross-bedded dolomitic siltstone lenses. This unit is usually less than 8 m thick and is a distinctive marker in the Beaver Dam Mountains. In section 2 this unit is composed of gypsiferous siltstone and is much thinner than in the other sections.

The upper unit is similar to the lower unit except it has more silt, less mud and gypsum, and worm burrows occur more often in the upper part than in the lower parts (fig. 10). The worm burrows were identified by Reif (1978) as belonging to *Rhizocorallium*. In the very upper part of this unit some thin beds of fine dolomitic siltstone occur.

The lower contact of the lower red member is an erosional unconformity with the underlying Harrisburg Member. The upper contact of the lower red member is the top of the stratigraphically highest mudstone unit beneath thick, resistant carbonate ledges assigned to the Virgin Limestone Member. Sometimes the lowermost Virgin Limestone beds are light yellowish brown siltstone units that grade into limestone units. The thickness of the lower red member in the Beaver Dam Mountains ranges from 0 to 67.7 m.

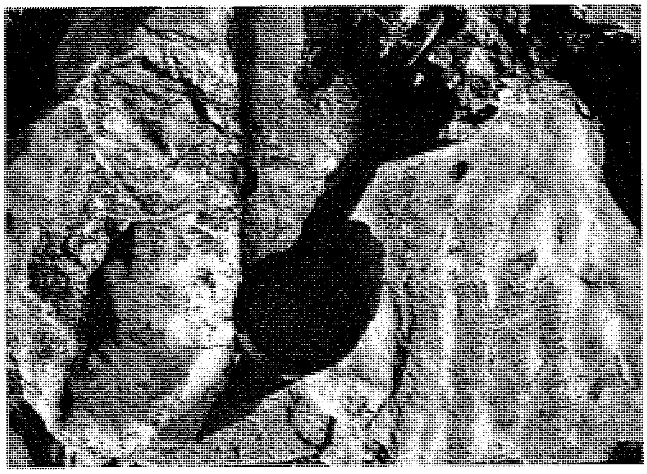


FIGURE 9.—*Ripple marks in the lower red member. Shown here are two different sizes. The ripples on the left have a wavelength of about 5 cm, and the ripples on the right have a wavelength of about 2 cm. Photograph from lower red member, section 2, approximately 45 m above the base.*

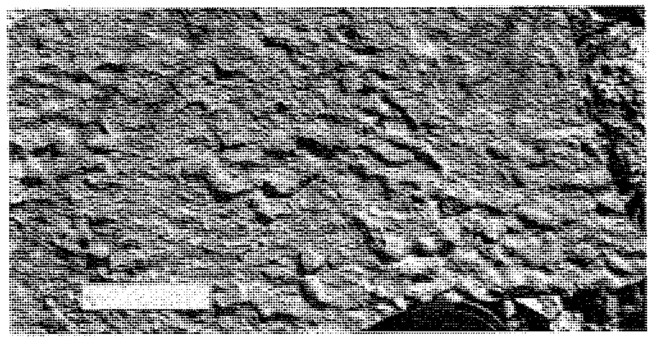


FIGURE 10.—*Numerous horizontal worm burrows on the underside of a thin siltstone unit of the lower red member. Photograph from lower red member, section 2, approximately 50 m above base. Bar scale is 5 cm.*

Virgin Limestone Member

The Virgin Limestone Member is readily identified in the Beaver Dam Mountains by several distinctive cliff-forming limestone horizons interbedded with nonresistant siltstone and mudstone, and by its distinctive yellowish brown color (fig. 11). The lowest limestone ledge contains abundant *Pentacrinus* fragments, allowing it to be easily identified (fig. 12). In the Beaver Dam Mountains the Virgin Limestone Member is composed of approximately 20% limestone and 80% siltstone and mudstone. The limestone beds occur as ledges 1 to 5 m thick, and are yellowish brown to medium gray. Normally there are three or four ledges formed by the Virgin Limestone Member on the east side of the Beaver Dam Mountains. Poborski (1954) stated that the ledges have sharp basal contacts and gradational upper contacts with the siltstone and mudstone units, but in section 6 the siltstone layers grade upward into the limestone ledge.

The limestone units are composed of pelloids, ooids, intraclasts, chert nodules, and shell fragments usually in a matrix of calcite cement. Dolomite and ferroan dolomite rhombs occur sporadically within the limestone ledges, as does nodular or lenticular chert. The fossil fauna is quite diverse in the limestone ledges and includes echinoderms, bivalves, gastropods, brachiopods, and ostracods.

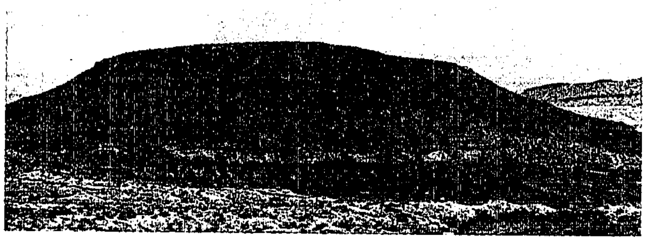


FIGURE 11.—*The distinctive weathering style of the Virgin Limestone Member is shown here. The hills with the ledges are part of the Virgin Limestone Member. Photograph taken looking northeast approximately 300 m southwest of section 7.*

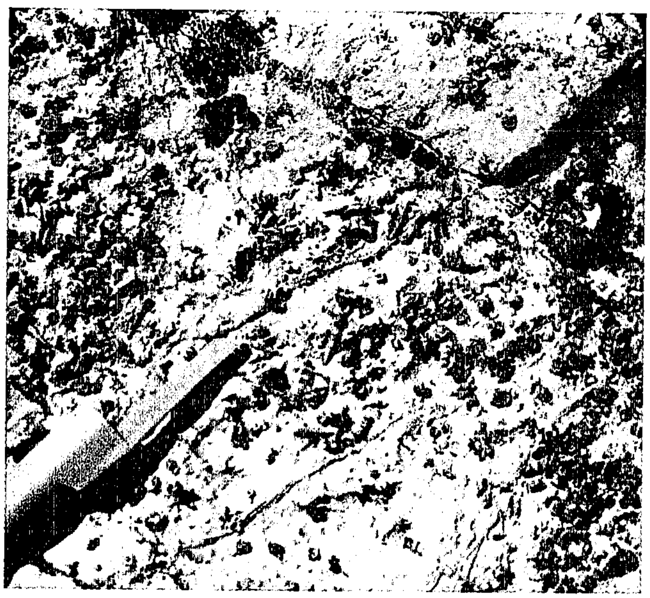


FIGURE 12.—Pentacrinus *fragments occur in most of the ledges of the Virgin Limestone Member. In this picture the* Pentacrinus *fragments are silicified, allowing them to weather out of the rock. Photograph from the Virgin Limestone Member, section 4.*

The echinoderm fragments consist of echinoid plates and spines, and star-shaped stem ossicles.

The siltstone and mudstone beds of the Virgin Limestone Member are either dark reddish brown, grayish brown, or yellowish brown. In most outcrops these rocks form a crumbly slope that makes it difficult to observe sedimentary structures. The rock is poorly lithified and breaks into pea-sized pieces when handled. Abundant bivalve shell fragments were found sporadically throughout the mudstone units and burrowing by bivalves probably partially accounts for the lack of sedimentary structures. Shorb (1983) observed trough cross-stratification, ripple cross-stratification, and planar bedding, and stated that, "Evidence of bioturbation is recognized in siltstones as prominent vertical escape structures of organisms." The siltstone and mudstone units are 1.2 to 24.7 m thick and form nonresistant slopes between the limestone ledges.

The lower contact of the Virgin Limestone Member is conformable with the lower red member where the lower red member occurs in the Beaver Dam Mountains. Where the Virgin Limestone Member lies directly on the Harrisburg Member the contact is an erosional unconformity and in places a soil horizon occurs between the Harrisburg and Virgin Limestone Members[1]. The upper contact of the Virgin Limestone Member is gradational with the middle red member and was taken to be the top of the resistant ledge at the base of the reddish brown mudstone beds that are so characteristic of the red beds of the red members of the Moenkopi Formation. The thickness of the Virgin Limestone Member ranges from 60.7 to 77.0 m.

Middle Red Member

The middle red member is similar to the reddish brown siltstone and mudstone beds of the lower red member and its color sets it apart from the Virgin Limestone and Shnabkaib Members. In most of the measured sections this member was either partially covered by alluvium and/or it formed a backslope so that only section 6 of the measured sections provided good outcrops of this member. At locality 6 reddish brown siltstone and mudstone constitute approximately 85% of the member with the rest mainly gypsum and dolomite. The reddish brown mudstone beds are either horizontally laminated with some lenticular bedding or structureless. Reif (1978) mentioned that some of the mudstones beds were structureless, but that most had microsedimentary structures when prepared as a polished section. The structureless nature of some of the mudstone beds may be due to the uniformity in grain size, bioturbation of the sediments prior to lithification, or to being obscured by the abundant stringers of secondary gypsum. The mudstone beds are usually crumbly, forming pieces less than 1 cm across.

The reddish brown siltstone beds usually have bimodal cross-bedding with some flaser bedding and rhythmically laminated bedding. The cross-bedding is very small-scale, having a wavelength of 2 to 4 cm and an amplitude of 1 cm or less.

[1]No sections were measured where the Harrisburg Member was in contact with the Virgin Limestone Member, but the contact between them was examined at the following location: NW 1/4, SE 1/4, NW 1/4, section 28, T. 42 S, R. 17 W. The contact is located approximately 4 km from Utah 91 on the Utah 91 Loop Road. The road in thesis area is built on the lowest ledge of the Virgin Limestone Member and the contact between the Harrisburg and Virgin Limestone can be examined approximately 50 meters west of the road.

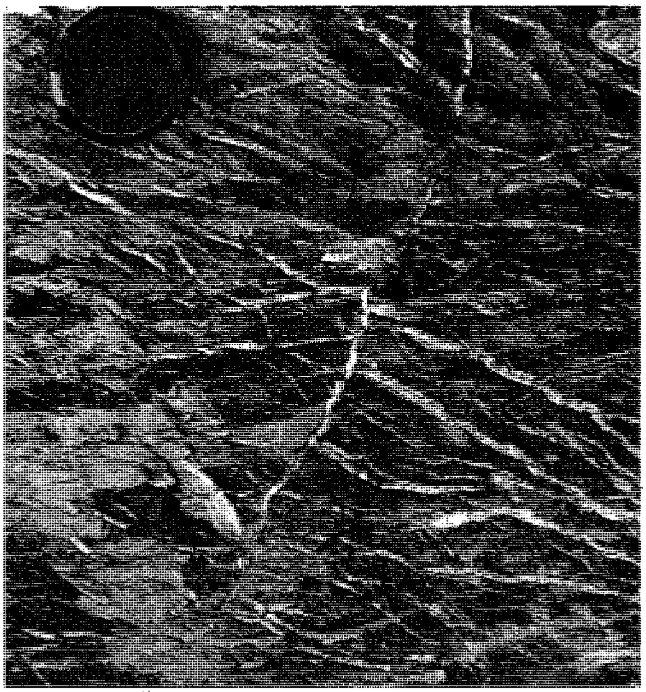


FIGURE 13.—*Stringers of secondary gypsum are abundant in the middle red member. They are thicker here than in the lower red member. Photograph from the middle red member, section 6, approximately 196 m above base.*

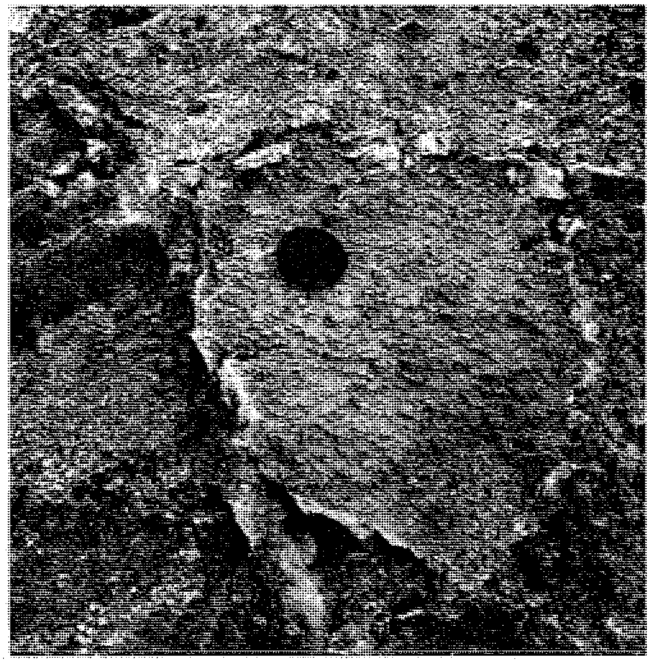


FIGURE 14.—*Mud cracks and tepee structures are common in the gypsum beds of the Shnabkaib and Harrisburg Members. Photograph from the Harrisburg Member, section 1, approximately 85 m above base.*

Gypsum occurs most often as stringers crisscrossing throughout the member (fig. 13). It also occurs in places as a matrix or cement for the siltstone and mudstone, being olive green and forming very hard slabs or ledges. Beds of gypsum begin to appear in the upper part of the member and they become thicker and more numerous near the top.

Dolomite beds occur throughout the member, but become more numerous toward the top. The thin beds are very light gray to light gray and are either laminated or have small-scale cross-bedding with some beds showing well-preserved ripple marks.

The upper contact of the middle red member is conformable with the Shnabkaib Member and was taken at the base of the first dolomite ledge or cliff-forming unit. The thickness of the middle red member ranges from 95.3 to 122.0 m.

Shnabkaib Member

The Shnabkaib Member is the thickest member of the Moenkopi Formation in the Beaver Dam Mountains. It is easily identified by its characteristic white strata and low-lying white hills. The Shnabkaib Member is composed predominantly of gypsum and it weathers so completely that exposures are frequently poor, often covered by a gypsiferous crust. Other lithologies include mudstone, dolomite, and lesser amounts of limestone and siltstone.

The gypsum is laminated to thin bedded, very light gray to bluish gray, and may form ledges or slopes. A chicken wire nodular pattern is common in outcrop, as are mud cracks and tepee structures (fig. 14). Cross-bedded gypsum occurs occasionally. It is composed of detrital gypsum and forms lenticular layers. The bedded gypsum is primary, but there are also some secondary gypsum stringers found throughout the member. Gypsum flowage structures are common throughout the Shnabkaib Member, but the relief is generally small and does not affect the overlying upper red member sediments.

The dolomite crops out as thin beds, usually less than 0.5 m thick, but some are up to 2 m thick. They are either thin bedded, cross-bedded, or show ripple laminations. Fossils were observed in several beds, some being continuous throughout the Beaver Dam Mountains. The fossils consisted of *Pentacrinus* fragments, gastropods, and bivalves. In places the fossils are silicified and almost entirely weathered out of the rock. Larsen (1966) stated that molluskan fossils are present, but very poorly preserved.

Mudstone and siltstone units in this member are typically pale red, poorly cemented with dolomitic cement, and in several horizons contain intraclasts. These rocks are either laminated, cross-bedded, or ripple laminated with some showing well-preserved ripple marks. Dolomitic siltstone beds that are light tan with small-scale cross-bedding occur frequently in the middle part of the member.

The upper contact of the Shnabkaib Member is conformable with the upper red member and was taken at the top of the last thick unit of gypsum at the base of the reddish brown siltstone and mudstone beds of the upper red member. The thickness of the Shnabkaib Member ranges from 188.8 to 260.7.

Upper Red Member

The upper red member is the thickest red bed member in the Beaver Dam Mountains. It is similar to the lower and middle red members, but it contains more siltstone and some sandstone. The upper red member generally has the best exposures of the red bed members in the Beaver Dam Mountains due to the overlying resistant Shinarump Conglomerate. Numerous cross-bedded siltstone and sandstone lenses occur throughout the member, and they become more numerous in the upper part of the member. Secondary gypsum stringers are abundant in the lower and middle parts of the member. The measured sections of this study ended at the base of the upper red member so this member was not measured. The upper contact of the upper red member is an erosional unconformity with the overlying Shinarump Conglomerate. The thickness of the upper red member ranges from 146.3 to 158.5 m (Stewart and others 1972).

LITHOFACIES

INTRODUCTION

Seven lithofacies were recognized in the study area:

1. gypsum
2. mudstone
   a. light gray dolomitic mudstone
   b. reddish brown dolomitic mudstone
   c. calcareous mudstone
3. siltstone
   a. reddish brown siltstone
   b. light tan dolomitic siltstone
   c. yellowish brown siltstone
4. dolomite
5. silty wackestone
6. fossiliferous wackestone
7. pelletal-ooidal grainstone to packstone

DESCRIPTION OF LITHOFACIES

Gypsum

Gypsum is the predominant constituent of both the Harrisburg and Shnabkaib Members and occurs throughout the other members of the Moenkopi Formation. Most of the gypsum is primary, but veins and stringers of secondary gypsum crosscut bedding planes in most of the members. The gypsum is a very light gray to light greenish gray and forms laminated beds that can be more than 3 m thick. A chicken wire pattern, mud cracks, tepee structures, and stromatolites are common in rocks associated with the gypsum facies. Nodules, flecks, or inclusions of gypsum are common in hand samples and thin sections. Intraclasts, occasional oolites, and rare crinoid fragments are also seen in thin section. Reif and Slatt (1979) observed dolomite intraclasts, ooliths, and skeletal fragments in the gypsum. Sedimentary structures observed in the gypsum beds are laminated bedding, convolute bedding, ripple bedding, and small-scale cross-bedding. Shorb (1983) also noted the presence of small-to medium-scale cross-bedding and calcitic boxwork structures in eastern Nevada.

Interpretations. Primary gypsum makes up more than 85% of the Harrisburg Member. The gypsum is predominantly laminated, indicating that it formed in a body of standing water, such as a brine pan (Cheevers and Rawson 1979), but the occurrence of mudcracks suggest some subaerial exposure. Similarly, the formation of a chicken-wire gypsum is believed by Mathews (1974) to be due to subaerial processes. These processes together would seem to indicate that the area of deposition might have been a supratidal flat of a sabkha, with periodic submergence and exposure.

Primary gypsum in the Moenkopi Formation was deposited in both clastic and carbonate tidal flat settings. The gypsum in this formation is also predominantly laminated with a chicken wire pattern. The presence of rip-up clasts and oolites indicates periodic submergence whereas the chicken wire pattern, stromatolites, and mudcracks indicate subaerial exposure. These conditions are met on supratidal flats, sabkha playas, and salt pans (Shinn 1983). Detrital gypsum is cross-bedded and was probably deposited by eolian processes on the supratidal flats. Secondary gypsum occurs as coarse satin spar and is very abundant in the lower and middle red members and formed as a postdepositional diagenetic event.

Mudstone

Mudstone is an important constituent of the Harrisburg Member and constitutes the bulk of the clastic sediment in the Moenkopi Formation (Reif 1978). Dolomitic mudstone occurs in the Harrisburg Member, lower red member, middle red member, and Shnabkaib Member. The dolomitic mudstone is of two types. The first type is very light gray, laminated to thin bedded with some areas being structureless. It is crumbly to flaggy, usually nonresistant, and contains abundant intraclasts and some shell fragments. The intraclasts are composed of mud or gypsum. Mud cracks and tepee structures occur occasionally. The second type of dolomitic mudstone is found in the red members of the Moenkopi Formation. It is reddish brown, usually structureless, crumbly, forms pea-sized pieces when handled, and weathers to form slopes. In some areas, such as the lower portion of the lower red member of section 2, intraclasts may be abundant. Where sedimentary structures can be observed, the mudstones are laminated with lenticular bedding, wavy bedding, rare mud cracks and tepee structures, and worm trails and burrows. Reif and Slatt (1979) also described pin-striped tidal bedding and slump structures in the mudstone units.

Calcareous mudstone occurs in the red beds of the Moenkopi Formation and in the Virgin Limestone Member. Calcareous mudstone is similar to the second type of dolomitic mudstone, being reddish brown, usually structureless, and crumbly, forming a nonresistant rubbly slope. In the red bed members where sedimentary structures can be seen, the mudstone layers are laminated with lenticular bedding; wavy bedding and worm burrows and trails are occasionally observed. In the Virgin Limestone Member nearly all of the mudstone is moderate reddish brown to moderate gray and falls apart into ellipsoidal-shaped fragments when handled. Abundant clumps of bivalve shell fragments are found sporadically throughout the unit. Small, light-colored mica flakes can be seen in hand samples. Mineralogically, the mudstone beds are composed of quartz, feldspar, clay minerals, and muscovite (Shorb 1983).

Structure type	NORTH SEA Mud Flat	Mixed Flat	Sand Flat	This Study
MUD BANK				
Without lamination	14	2	0	45
With silty laminations	17	3	0	15
Silty mud	11	7	0	12
LAMINATED BEDDING				
Fine	10	18	3	10
Coarse	3	24	2	2
LENTICULAR BEDDING	1	9	1	2
FLASER BEDDING	5	13	13	4
RIPPLE BEDDING				
Short-wave	0	2	54	0
Mega	0	0	5	0
LAMINATED SILT	0	1	10	0
BIOTURBATE STRUCTURE	39	21	12	10

FIGURE 15.—*This figure shows the abundance of sedimentary structure types on a North Sea tidal flat (Reineck 1967) and the abundance of sedimentary structure types observed in this study in the red bed members of the Moenkopi Formation. The numbers are percent volume and they are approximate for this study.*

Interpretations. Dolomitic and calcareous mudstone beds of the Harrisburg Member and Moenkopi Formation are interpreted to represent deposition on muddy tidal flats (Reif and Slatt 1979). Reinek (1967) described the types and percentage of sedimentary structures occurring on the modern-day North Sea tidal flats. He indicated that in the mud flat part of the tidal flats the most common type of structures are the mud banks and bioturbate structures, with a small percentage of fine rhythmically laminated bedding (fig. 15). Triassic rocks of this study show that the most common type of sedimentary structures are mud banks or structureless units, laminated bedding, evidences of bioturbation, and some lenticular bedding (fig. 15). Mud cracks and tepee structure formation take place on high intertidal or supratidal mud flats (Reif and Slatt 1979). Worm burrows and trails and bivalve shells indicate that the depositional environmental characteristics were not overly harsh, but variable enough that few organisms lived there.

Siltstone

This lithology is found in all members studied. Siltstone beds of the red bed members differ in many aspects from the siltstone beds of the carbonate members, therefore, they will be treated separately.

Red bed siltstone layers in both the lower and middle red members generally weather to form ledges or overhangs, which are sandwiched between layers of mudstone. They are thin to thick bedded and may exhibit a variety of sedimentary structures, including small- to medium-scale cross-bedding, bimodal ripple marks, flaser bedding, and/or interference ripples. In some places the siltstone layers were structureless, sometimes with evidences of bioturbation. In addition, Reif (1978) noted double-crested ripples, parallel ripples, undulatory and lingoid small ripples, convolute bedding, mud cracks, and raindrop impressions. The siltstone can be cemented by either calcite or dolomite or a mixture of the two.

Carbonate member siltstone layers occur in two varieties: (1) a light tan, small-scale, cross-bedded, dolomitic siltstone, and (2) a yellowish brown, grayish or reddish, thin- to thick-bedded siltstone. The light tan siltstone layers occur only in the Harrisburg and Shnabkaib Members. These siltstone layers are usually thin, dolomitic, and are almost always associated with the gypsum or dolomitic mudstone beds. Sedimentary structures of these units include micro- to small-scale cross-bedding, lenticular beds, undulating or unconformable upper and

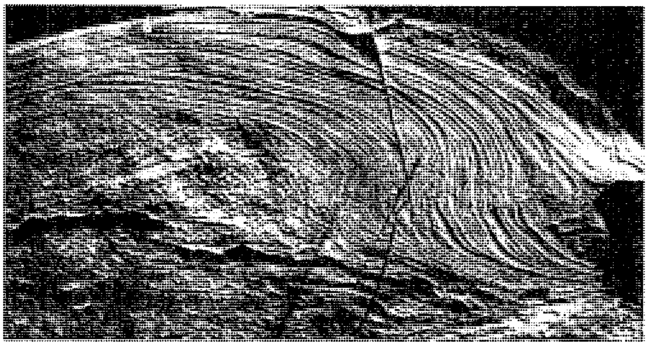


FIGURE 16.—*Convolute bedding in a dolomitic siltstone unit of the Shnabkaib Member. The rock is 1/2 m long. Photograph from the Shnabkaib Member, section 3, unit 21.*

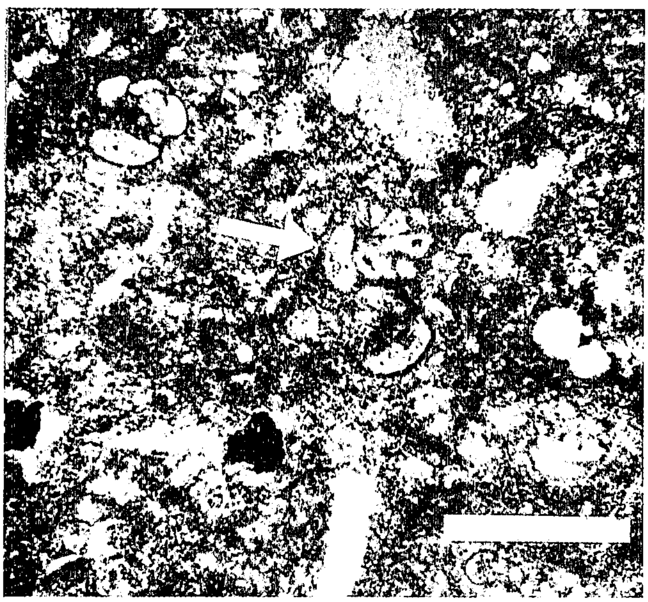


FIGURE 17.—*Photomicrograph of foraminifera and crinoids from the Harrisburg Member, section 1, approximately 16 m above base. Arrow points to a foraminifera. Bar scale is 1 millimeter.*

lower surfaces, and convolute bedding (fig. 16). They are composed almost entirely of quartz grains and are well sorted.

The yellowish brown to reddish siltstone layers occur in the Virgin Limestone and Shnabkaib Members. These units are variable in thickness, calcareous to dolomitic, thin to thick bedded, or structureless and poorly cemented. In the Virgin Limestone Member the siltstone layers occur beneath the first limestone ledge and above the top limestone ledge in sections 3 and 4. These units are usually thin to medium bedded, yellowish brown with abundant limonite flecks and ripple marks. The thin beds may alternate with thin units of mudstone.

The grayish or reddish siltstone layers occur in the Shnabkaib and Harrisburg Members and range substantially in thickness. The layers may be thin to thick bedded or structureless. Sedimentary structures include cross-lamination and small- to medium-scale cross-bedding, which may grade upwards into very thin-bedded micro-cross-bedded and rippled siltstone. In a similar lithofacie in eastern Nevada, Shorb (1983) observed slump structures or soft-sediment deformation features, and vertical escape structures.

Interpretations. Red bed siltstone layers are interpreted as being deposited on intertidal flats by shallow tidal channels. This interpretation is based on the small- to medium-scale cross-bedding, the thinness of the siltstone units and their lateral continuity, the amount of bioturbation, and the types of ripple marks. Reif and Slatt (1979) stated that widely varying conditions of water depth, sediment supply, and current strength in the environment would produce the diverse array of ripple-mark types found on the siltstone bedding planes. However, the fact that siltstone is not abundant suggests that tidal channels were not a dominant feature on the muddy tidal flat.

The light tan siltstone layers are interpreted as being deposited on supratidal flats by eolian processes. The well-sorted nature of the quartz grains, lack of ripple marks and channeling, and occurrence on the supratidal flat areas suggest that they were deposited by wind rather than water processes. These rocks were dolomitized after deposition on the supratidal flat by basically the same processes as the dolomitic mudstone units.

The yellowish brown, grayish or reddish siltstone layers of the carbonate members represent deposition on the upper part of a shallow marine shelf. Shorb (1983) stated that fluctuations in clastic sediment supply, sea level, subsidence, and possibly temperature and salinity gradients dictated the presence of dominantly carbonate or clastic environments. The sedimentary structures indicate shallow water and intertidal deposition. Cross-bedded strata of small- to medium-scale are indicative of intertidal channels; thin-bedded, microcross-bedded layers are suggestive of intertidal flats. Reif and Slatt (1979) suggested that the slumping and soft-sediment deformation structures occurred along intertidal channel walls as a result of gravity sliding.

Dolomite

Dolomite is an important constituent of the Harrisburg and Shnabkaib Members and some parts of the upper Virgin Limestone Member are partially dolomitized. The dolomite beds are closely associated with primary gypsum beds. Most of the dolomite beds are fine-grained, very light gray, and form resistant ledges. Associated

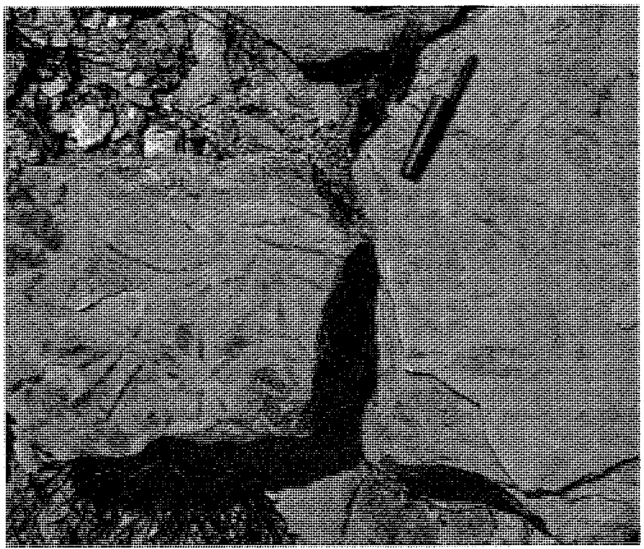


FIGURE 18.—*A burrowed dolomite of the Shnabkaib Member. Photograph from section 3, unit 24.*

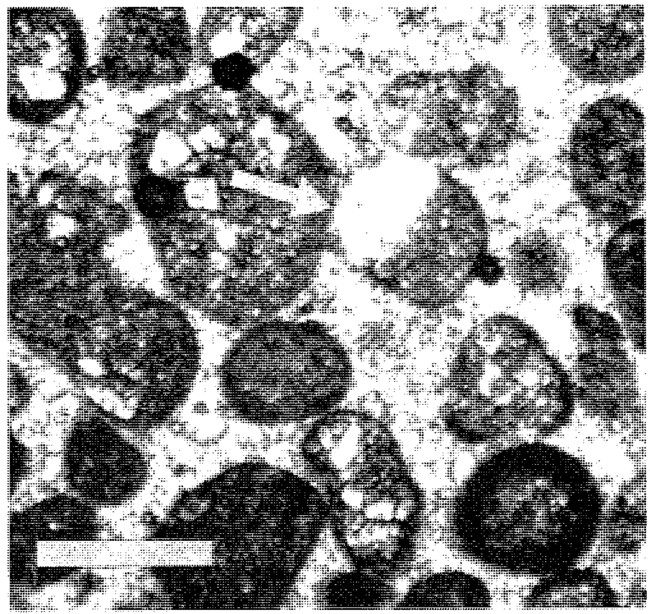


FIGURE 19.—*Photomicrograph of dolomite rhombs in the centers of coated grains. Moldic porosity occurs in the right center of the photo where 1/2 of a coated grain is missing (shown with an arrow). Most of the grains are coated with a micritic sheath. Photograph from the Virgin Limestone Member, section 6, approximately 129 m above base. Bar scale is 500 microns.*

allochems are crinoid and bryozoan fragments, foraminifera, gastropods, bivalves, quartz grains, pellets, ooids, intraclasts, algal material, and chert noduals (fig. 17). Reif (1978) observed that the dolomite beds contain alternating silty laminae that have upward fining, graded bedding. Stromatolites and wispy algal material occur in outcrop and thin section, appearing in outcrop as wavy laminated bedding. In the dolomite lithofacie of these same members in eastern Nevada, Shorb (1983) noted that some of the dolomites exhibit irregular fenestral porosity resembling birdseye structures. Sedimentary structures associated with the dolomite layers include laminated bedding, wavy laminated bedding, thin to medium bedding, vugs, burrows, and occasional dessication cracks (fig. 18). Some of the intraclasts, which are formed of mud, in the dolomite layers may have been mudcrack polygons that escaped early dolomitization (Shinn 1983). Reif (1978) observed antiform structures which he interpreted as tepee structures.

In many beds of the Shnabkaib Member and in the upper ledge of the Virgin Limestone Member large rhombs of euhedral dolomite are common. They range from 60 up to approximately 190 microns in diameter (fig. 19). Where the dolomite occurs as a cement the euhedral rhombs are commonly 1 to 25 microns across and can be up to 45 microns across. Ferroan dolomite rhombs occur frequently in the upper ledge of the Virgin Limestone Member, and they can be as large as 270 microns wide (fig. 20). Shorb (1983) observed ferroan dolomite rhombs in the Shnabkaib Member that were approximately 50 microns in size. He also recognized a dolomitized shell fragment coquina in eastern Nevada.

Interpretations. Dolomite units of the Harrisburg and Shnabkaib members are interpreted as having formed in a tidal flat setting. This interpretation is based largely on the sedimentary structures and associated sediments. Shinn (1983) stated that stromatolites are normally preserved only in the upper intertidal to supratidal range, as

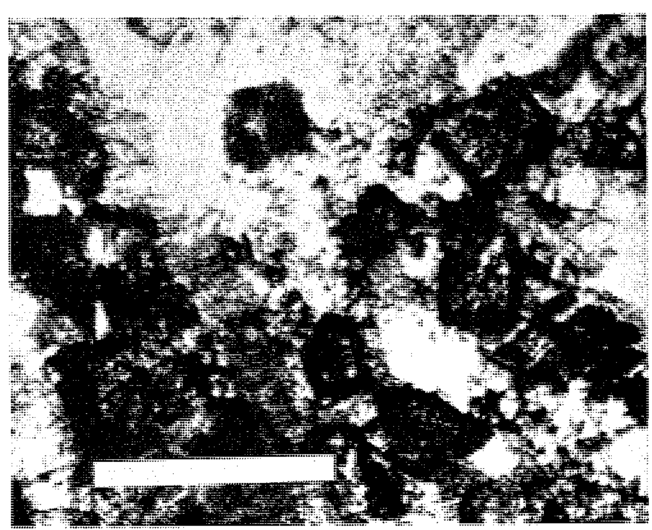


FIGURE 20.—*Photomicrograph of ferroan dolomite rhombs from the Virgin Limestone Member, section 6, approximately 128 m above base. Bar scale is 500 microns.*

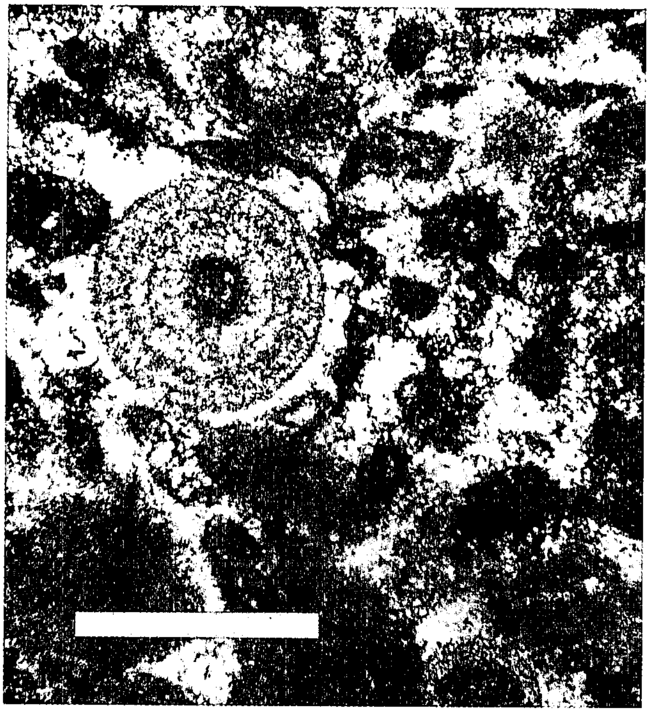


FIGURE 21.—*Photomicrograph showing the abundant, small, irregularly shaped intraclasts (in this part of the thin section) from the silty wackestone facies. In the center of the photo is a well-preserved concentric ooid. Photograph from the Virgin Limestone Member, section 2, approximately 113 m above base. Bar scale is 500 microns.*

are laminated sediments, due to bioturbation in the intertidal and subtidal areas.

Marlay (1983) concluded that the most reasonable mechanism for dolomitization of the Shnabkaib Member was a variant of the seepage reflux model that is operative on prograding tidal flats. Patterson and Kinsman (1982) discussed the formation of diagenetic dolomite in a coastal sabkha along the Arabian (Persian) Gulf using a type of seepage reflux model. This model requires the gradient of the tidal flat or coast to be very low, allowing onshore winds to periodically propel thin sheets of seawater inland (Patterson and Kinsman 1982). Precipitation of gypsum increases the Mg^{++}/Ca^{++} ratio to as high as 100, and the water moves inland until depleted by evaporation and infiltration or until the wind diminishes (Patterson and Kinsman 1982). Infiltration of Mg^{++}-enriched brine causes dolomitization in the high intertidal and supratidal zones (Patterson and Kinsman, 1982). Storm tides could also cause the periodic flooding of the sabkha.

Silty Wackestone

Most of the limestone in the Virgin Limestone Member may be classified as silty since it contains varying amounts of silt grains, but the limestone rock units containing a large portion of silt grains are ledges 3 and 4 of section 2 and ledge 3 of section 6. The silty wackestone units are usually light yellowish to medium gray and thin to thick bedded. The silt grains are composed of quartz, are subangular to subrounded, and are uniform in size averaging approximately 30 microns in diameter. The silt grains may be microcross-bedded to small-scale cross-bedded and may have flaser bedding on a microscopic scale. Silt grains constitute 30%–40% of the rock. Micrite and microsparite constitute the major portion of the rock making up about 35%–40% of the volume. Intraclasts are spread sporadically throughout the rock and are small, irregularly shaped micrite or mud blebs (fig. 21).

Calcite cements the silty wackestone with no dolomite or silica cement seen in thin section. Small poorly preserved cubes of pyrite that is being oxidized to hematite occurs throughout much of the rock. They appear as small (less than 70 microns), very dark, partially oxidized cubes that usually have some brown solution-looking material surrounding them. The porosity of these rocks is fairly high, being as much as 15% in section 3, and it is mainly interparticle porosity occurring between the silt grains.

Interpretations. The silty wackestone units are interpreted as having formed in the low intertidal zones of a carbonate tidal flat. This is based on the light color of the rock, the sedimentary structures, associated sediments, and the amount and type of intraclasts. Features that are the most diagnostic of the subtidal, intertidal, and supratidal environments of a carbonate tidal flat are listed in figure 22. Lack of mud cracks, tepee structures, stromatolites, evaporites, dolomites, birdseye vugs, and dessication cracks reduces the possibility of the silty wackestone facies being high intertidal or supratidal. The subtidal rocks are generally darker than intertidal and supratidal rocks due to reduction and organic content (Shinn 1983). The silt grains were carried into the intertidal facies by eolian or fluvial processes.

Fossiliferous Packstone

Fossiliferous packstone units form the lower two limestone ledges in all of the measured Virgin Limestone sections and part of the upper ledges in sections 4 and 6. The fossiliferous packstone units are yellowish gray to medium gray, thin to medium bedded or massive, and some show small-scale cross-bedding. The fossils are the broken stem and plates of *Pentacrinus*, bivalve and gastropod shell fragments, and bryozoans (fig. 23). The rest of the rock is composed of calcite cement, microsparite, pelloids, ooids, intraclasts, quartz silt grains, and iron oxide rhombs.

In sections 2, 3, and 4 the echinoderm fragments in some of the ledges have been silicified. Broken stems and plates of echinoderms weather out and, in places, protrude over 5 mm out of the rock, making these rocks some of the easiest to identify in the Beaver Dam Mountains (see fig. 12). Silicified bivalve and gastropod shell fragments are only found in small-scale cross-bed sets. The pelloids in the fossiliferous packstone units are generally ellipsoidal and about 170 microns in size. Normally they have a recrystallized microsparite center surrounded by a micritic sheath, but in some instances the centers have been dissolved, forming moldic porosity (see fig. 18). Where silica cementation occurs much of the porosity is filled in with silica. The intraclasts and iron oxides are similar to those found in the silty wackestones.

Interpretations. The fossiliferous packstone rocks are interpreted as shallow water bars, shoals, and banks. Cross-bedding, disarticulation and abrasion of grains, lack of micrite, and types of allochems indicate well-washed, high-energy environments (Shorb 1983). Hansen (1979) recognized a microfacies in a Mississippian crinoid shoal that represented the life environment of the echinoderms and another microfacies landward (the shoal itself), which represented the primary area of accumulation. Possibly the same process occurred in the Virgin Limestone Member, only the area of accumulation was observed in this study. The abundant cross-bedded units of other types of shells probably represent storm surges.

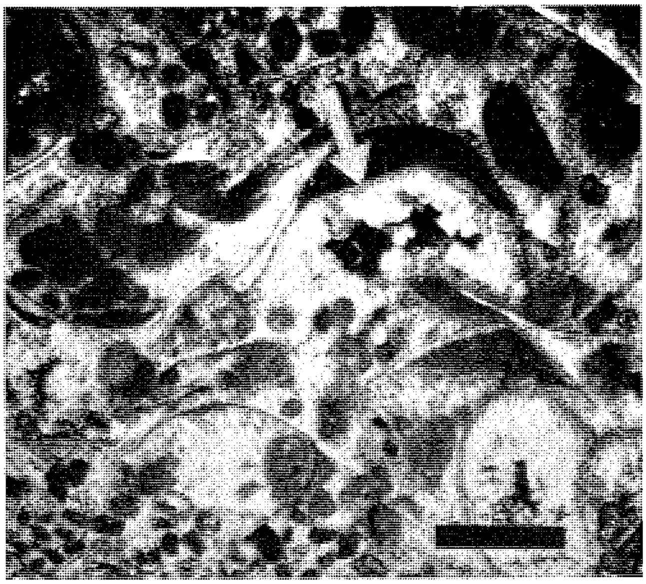


FIGURE 23.—*Photomicrograph of the fossiliferous packstone facies. Shelter porosity occurs under the bivalve shell in the center of the photo as shown by the arrow. Photograph from the Virgin Limestone Member, section 2, approximately 112 m above base. Bar scale is 1 millimeter.*

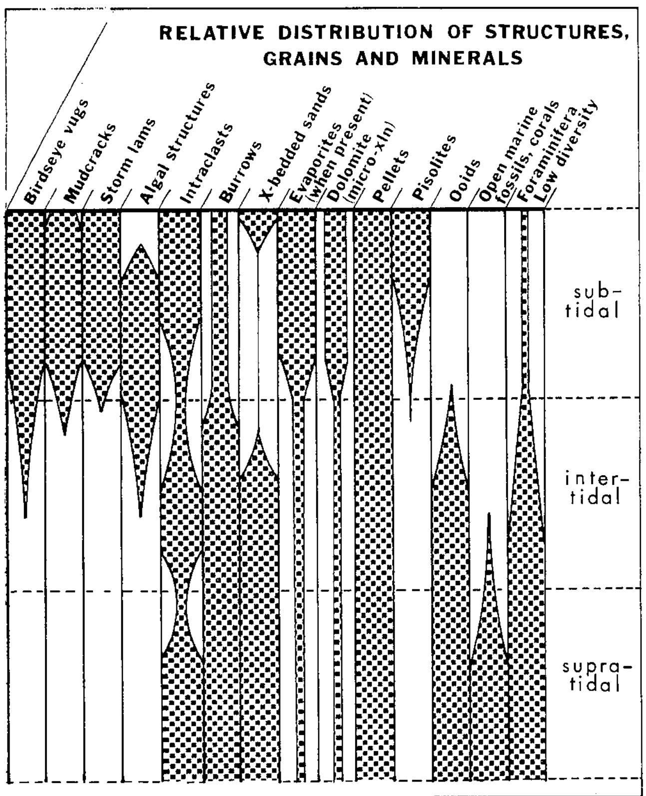


FIGURE 22.—*Table showing the relative distribution of structures, grains, and minerals in the subtidal, intertidal, and supratidal environments of a carbonate tidal flat (after Shinn 1983).*

Pelloidal-Ooidal Grainstone to Packstone

This kind of limestone occurs in the third ledge of section 2 and the top ledge of section 6 of the Virgin Limestone Member. It is light olive gray to medium light gray, medium to thick bedded with some massive units and much of it is small- to medium-scale cross-bedded. The pelloids and ooids range in size from 120 to 495 microns with the largest particles being concentric ooids (see fig. 21). There are more ooids than pelloids in most of the thin sections, but usually both are present.

The grainstones are not densely packed and they are relatively free of other types of allochems, containing intraclasts, silt grains, and some worm burrows. Shell fragments are rare to nonexistent in the pelloidal-ooidal grainstone to packstone rocks. The packstone units also were not densely packed, but they contained micrite, few to abundant intraclasts, silt grains, and worm burrows. The pelloids consist of fecal pellets and other types of coated grains. The coated grains often are coated with a micritic sheath and have dolomite rhombs in their centers (see fig. 19). Other features of the pelloidal-ooidal grainstone to packstone rocks are moldic porosity, stylolites, and spar-filled features.

Cement in these rocks is mainly chemically precipitated calcite cement. Fabric criteria for the cement follows Bathurst (1975) and include: (1) the spar is interstitial

FIGURE 24.—*A dolomite ledge of the Harrisburg Member. Chert nodules appear throughout the upper part of the ledge, but the chert has a honeycomb structure near the upper surface. Photograph from section 1, approximately 97 m above base.*

(interparticle) with well-sorted and abraded particles, which are in depositional contact with each other; (2) particles composed of micrite are not altered to spar; (3) micrite coats on particles are not altered to neomorphic spar; (4) mechanically deposited micrite is present but unaltered; (5) contacts between spar and particles are sharp; (6) the intercrystalline boundaries in the mosaic are made up of plane surfaces; (7) the size of the crystals increases away from the initial substrate of the sparry mosaic; and (8) the crystals of the sparry mosaic have a preferred shape orientation with the longest axes normal to the initial substrate of the mosaic. Some of the worm burrows appeared to be cemented with pore-filling equant calcite. Dolomite found in these rocks occurs as rhombs 70 to 290 microns in size, commonly in the centers of the coated grains. A slight amount of dolomite cement also occurs in some of the rocks.

Ooids in grainstone units consist of both concentric and radial forms. Davies and others (1978) stated that concentric ooids, or those with a tangential orientation of carbonate crystals, formed in agitated conditions whereas those with a radial orientation are more prevalent in quiet water. Most of the ooids in the grainstone to packstone rocks have a concentric structure.

Interpretations. The pelloidal-ooidal grainstone to packstone rocks are interpreted as forming in an oolite shoal complex. The grainstones make up the great bulk of the shoal and the packstones were deposited landward of the shoals (Shorb 1983). The shoal complex formed near wave base where the energy was high enough to winnow away the mud and smaller particles but leave the larger particles. This interpretation agrees well with Wilson's (1975) standard facies belts 6 and 7, in which he shows ooids or winnowed edge sands in belt 6, and landward in belt 7 are the coated grains in the shelf, lagoon, and open circulation belt.

CHERT

The terminology used for chert in the Kaibab and Moenkopi Formations is based on the amount of chert present and decribes its appearance in outcrop. Nodular chert refers to small rounded or spheroidal masses of chert. Layered or ribbon chert refers to elongate stringers or horizontal bands of chert, which form a sheet in 3 dimensions (fig. 24). The last type is disseminated chert which forms a honeycomb network within the limestone or dolomite units (Nielson 1982).

Chert as the main constituent of a unit only occurs in the Harrisburg Member in section 4, but lesser amounts of chert occur in almost all limestone and dolomite units. The chert unit in section 4 is reddish brown, medium to thick bedded, and very resistant. In thin section no fossil fragments or other structures were observed. Nielson (1982) noted that the nodular chert usually contains a sponge (Actinocoelia) in its center. The reddish chert unit is distinctive wherever it crops out in the Beaver Dam Mountains.

Nielson (1982) suggested that the deposition of chert occurred as a diagenetic process due to silica-rich solutions migrating through the units after calcite cementation but before dolomitization. Secondary silicification is also suggested by silica replacing crinoid fragments and silicification of a bivalve coquina rock. Silicification occurs sporadically in the ledges of the Virgin Limestone Member, whereas fossils occur throughout the ledges; this also suggests that the silicification was secondary. Silicified areas probably occurred where porosity, permeability, and other factors allowed percolation of migrating fluids in the rock.

DEPOSITIONAL MODEL

The upper Kaibab and Moenkopi Formations were deposited on a gently westward sloping shelf. In general the limestone, dolomite, and gypsum units were deposited during transgressions and the red bed members during regressions.

At the beginning of Harrisburg time, an overall regression of the seas began. The regression was probably due in part to prograding of the carbonate platform and in part to subsidence and eustatic sea level changes (Raup and Stanley 1978). Subsidence was important for the accumulation of thick sequences of laminated gypsum that occur in the lower and upper units of the Harrisburg Member. The middle unit was formed by repeated prograding of a carbonate bank, coupled with slow subsidence, forming alternating gypsum and dolomite layers. Similar conditions of dolomitization on a prograding coast are occurring along the south shore of the Arabian (Persian) Gulf today (Patterson and Kinsman 1982). Figure 25 shows the extent of the dolomite and gypsum facies during Harrisburg time.

During Guadalupian and Ochoan time, either sediments were deposited, uplifted, and eroded, along with much of the Harrisburg, or no sediments were deposited, but uplift and erosion formed a karst topography on the Harrisburg strata. McKee and others (1967) stated that these rocks were apparently uplifted in late Guadalupian time.

The next rocks to be preserved in the Beaver Dam Mountains are the red beds of the lower red member. These rocks were deposited in a muddy tidal flat environment similar to the Colorado River Delta (Thompson 1968). But throughout lower red time, hills of Harrisburg remained above lower red depositional levels. The fine grain size of the lower red member sediments may be due to (1) the type of rocks in the source area or (2) the position on the tidal flat. According to Reineck (1967) the upper part of the North Sea tidal flats is composed of mud, which grades into silt lower on the tidal flat. I favor the former because of the vast extent and thickness of the fine-grained sediments. Siltstone units within the lower red member represent tidal channels that migrated laterally across the tidal flat. Figure 26 shows a schematic representation of the depositional environments of the red bed members.

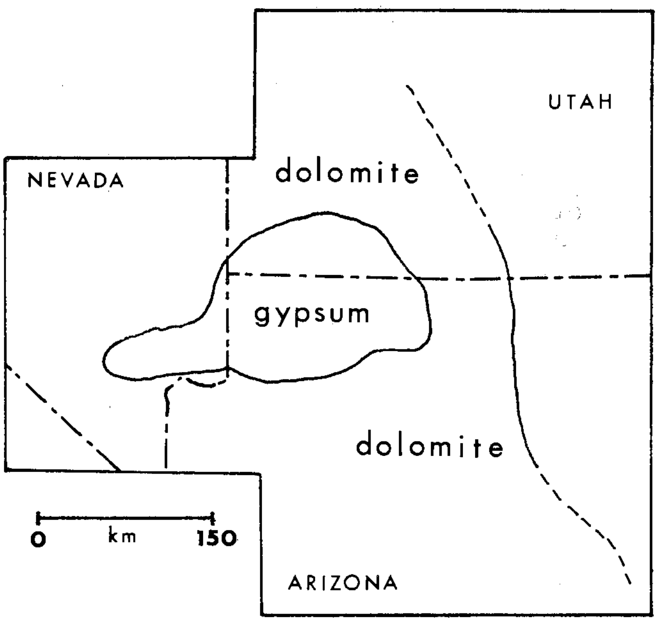


FIGURE 25.—*A diagram showing the facies relationships of the gypsum and dolomite facies at the beginning of Harrisburg time (modified after Cheevers and Rawson 1979).*

The transgressive Virgin Limestone Member sediments were deposited in a carbonate tidal flat setting. The clastic sediments that were being deposited in the area may have (1) shifted and were being deposited in adjacent areas, (2) were being deposited farther landward due to a rise in sea level, or (3) due to a lack of uplift in the source area were not being eroded, transported, or deposited. The Virgin Limestone Member contains two main depositional environments: a low intertidal and a low supratidal environment. The lower intertidal depositional environment was similar to the depositional environment described by Loreau and Purser (1973) in the Arabian (Persian) Gulf. They stated that the oolites are formed on tidal deltas and tidal channel edges, where they are temporarily maintained due to multidirectional currents, but are eventually distributed to adjacent barrier beaches, tidal channel bars, and lagoons.

The low supratidal sediments formed in an environment similar to the depositional environment of the modern-day Ojo de Liebre Lagoon area of Baja, California. The supratidal flats or brine pans are separated from the lagoon by low barriers of sand, shell fragments, and mud (Phelger 1969), similar to the silt and shell fragment shoals of the Virgin Limestone Member. Tidal channels extend through the barrier and a considerable amount of dust and sand is blown into the area (Phelger 1969). A large standing stock of organisms thrive in this environment, including algae, foraminifera, chlorophytes, and at times mollusks (Phelger 1969). In the supratidal flats of the Virgin Limestone Member a great abundance of organisms may also have been present, as noted by the occurrence of bivalve shells in the mudstone units and a lack of sedimentary structures. Temporary gypsum or salt growth may also have disrupted or destroyed bedding features. Wind-blown clastic material may have been blown onto the supratidal flats of the Virgin Limestone Member, but intermittent streams having a very fine-grained, suspended sediment load may also have deposited some of the muddy sediments on the supratidal flats. Figure 27 shows a schematic representation of the Virgin Limestone Member depositional environments.

The regressive middle red member sediments were deposited on a muddy tidal flat similar to that of the lower red member, and the Shnabkaib Member sediments were deposited in a transgressive carbonate tidal flat setting similar to that of the middle unit of the Harrisburg Member.

ECONOMIC GEOLOGY OF THE HARRISBURG MEMBER AND MOENKOPI FORMATION

The Kaibab and Moenkopi Formations have been explored for hydrocarbon and mineral resources. The petroleum industry has tested both the Kaibab and Moenkopi Formations. In the Harrisburg Member, oil shows have only been seen in the Pintura Anticline (Nielson 1982). The Harrisburg Member forms an excellent trap rock, composed mostly of gypsum, and has good source materials, stromatolites, and algae growing on the brine pans, sabkhas, and supratidal flats, but it has few good reservoir rocks. The only possibilities are dolomites or dolomitic siltstone units. The thickest dolomite units are only 3–4 m, with most of them being less than 1 m thick, and the dolomitic siltstone units are usually less than 1 m thick. Both the dolomite and dolomitic siltstone units have gypsum above and below, forming excellent stratigraphic traps for hydrocarbons. Other possible reservoir rocks may be collapse breccias. These structures may be several miles long, capped by either gypsum of the Harrisburg Member or mudstone of the lower red member, and have high porosity and permeability.

The unconformity between the Harrisburg Member and Moenkopi Formation may form an excellent hydrocarbon trap. Closure on the unconformity surface may be more than 180 m, and it is usually capped by the mudstone units of the lower red member. Possible reservoir rocks are the same as for the stratigraphic traps.

In the Moenkopi Formation oil production is confined to the Timpoweap and Rock Canyon Conglomerate members from the Virgin Oil Field (Nielson 1982). Other areas have been drilled with little or no success. The oolith grainstones of the Virgin Limestone Member would perhaps be good reservoir rock, underlain by semi–organic-rich shale and overlain by the same, but no oil shows have been reported from this member. The Shnabkaib Member may form stratigraphic traps, being similar to the Harrisburg Member of the Kaibab Formation.

High-displacement basin-and-range normal faults have uplifted the rocks, perhaps forming structural traps to the east.

Gypsum is the principal economical mineral in this area. Large gypsum lenses that were not altered by groundwater or erosion and dissolution at the end of the Permian Period in the Harrisburg Member would be the major target (Nielson 1982). Bulldozer pits are common on the east flank of the Beaver Dam Mountains.

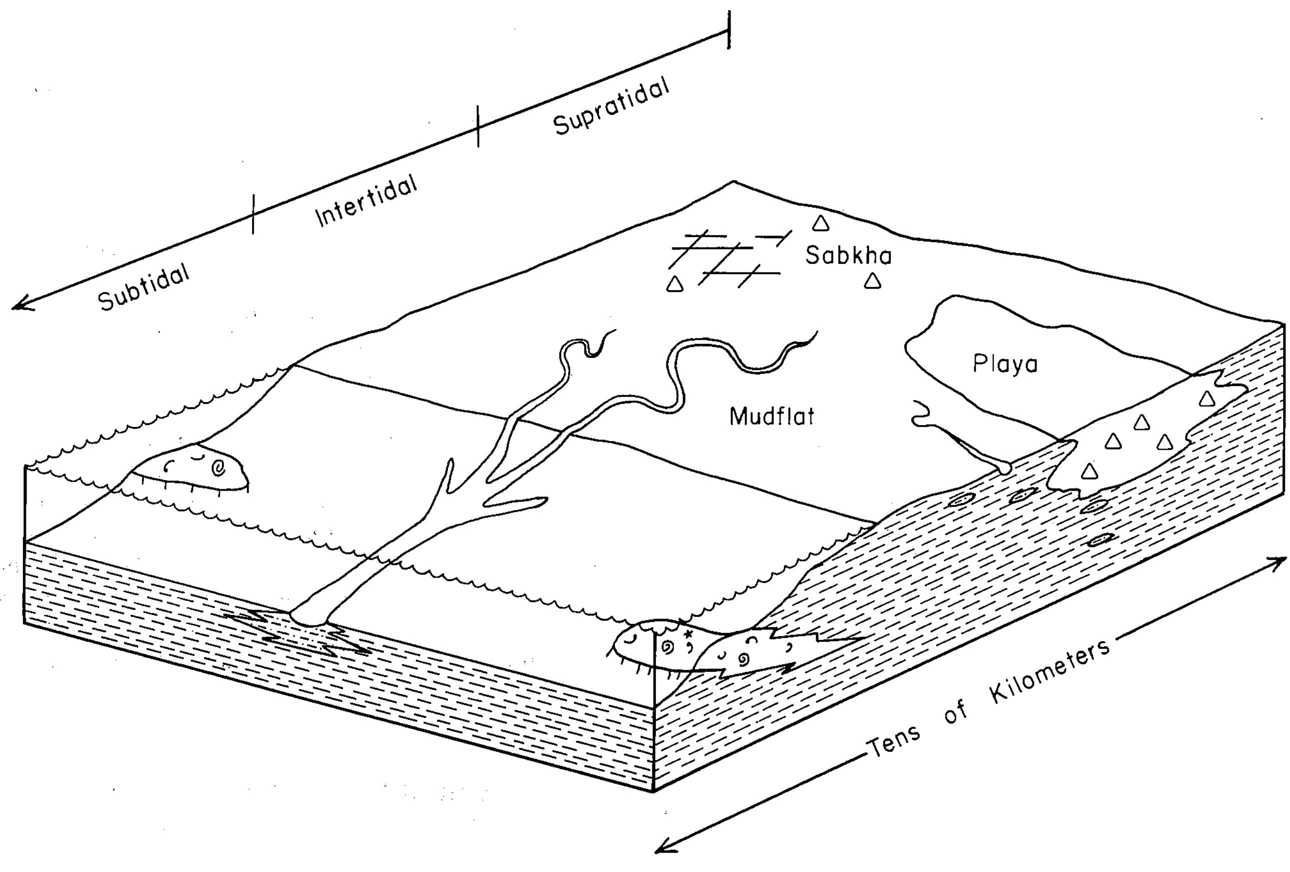


FIGURE 26.—*A schematic representation of the red bed member depositional environments.*

CONCLUSIONS

First, difficulty in tracing the Harrisburg Member in the Beaver Dam Mountains is attributed to two processes: (1) the formation of karst topography on the nonresistant gypsum beds of the Harrisburg strata in pre-Moenkopi time, and (2) solution activity in both pre-Moenkopi time and Recent time, forming collapse structures in the Harrisburg strata. These two processes cause the Harrisburg Member to range more than 170 m in thickness. At the end of lower red time, paleohills of Harrisburg remained as islands above the sea that accompanied deposition of the Virgin Limestone Member, but they were covered by strata of this member. The original thickness of the Harrisburg Member could not be determined, but it was greater than the thickest section preserved (181 m) in the Beaver Dam Mountains.

Second, members of the Moenkopi Formation are present in the Beaver Dam Mountains. They are, in ascending order: lower red, Virgin Limestone, middle red, Shnabkaib, and upper red. The base and top of the formation are erosional unconformities, but the contacts between members are conformable. The Timpoweap Member is not present in the Beaver Dam Mountains.

Third, following facies are present in the Harrisburg Member and lower Moenkopi Formation: (1) gypsum, (2) mudstone, (3) siltstone, (4) dolomite, (5) silty wackestone, (6) fossiliferous packstone, and (7) pelloidal-ooidal grainstone to packstone. The gypsum was deposited under supratidal conditions. The dolomitic and calcareous mudstone and siltstone units were deposited on muddy, clastic, and carbonate tidal flats. The dolomite formed under supratidal conditions by a variant of the seepage reflux method on a prograding carbonate bank. The silty wackestone units formed in the low intertidal zone of a carbonate tidal flat. The fossiliferous packstone units formed in shallow water bars, shoals, and banks, and the pelloidal-ooidal grainstone to packstone rocks formed in an oolite shoal complex.

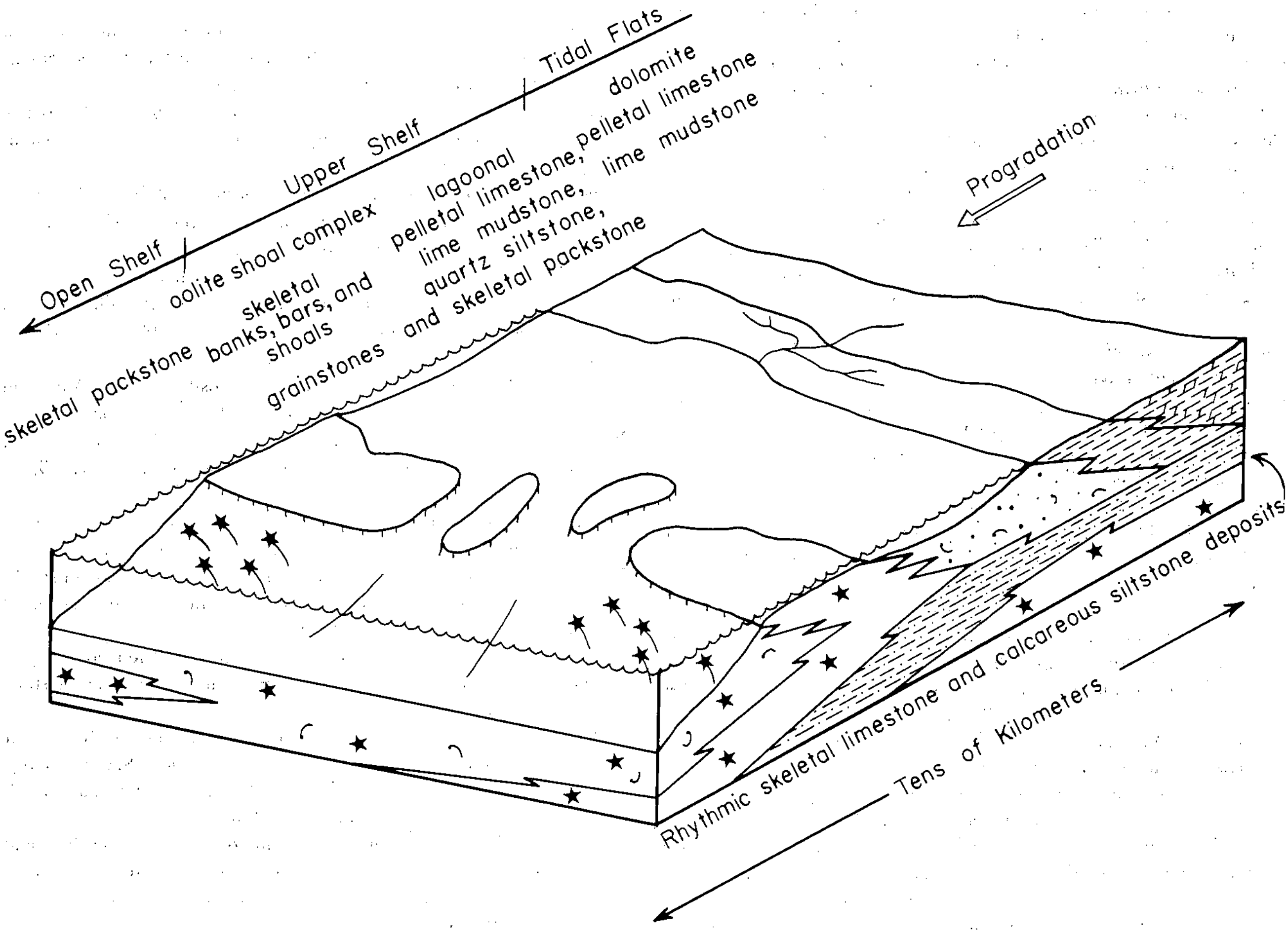


FIGURE 27.—*A schematic representation of the Virgin Limestone Member depositional environments (modified after Shorb 1983).*

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