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Sedimentology and sequence stratigraphy of the Chinle Formation, southern Utah

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SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY OF THE CHINLE FORMATION, SOUTHERN UTAH

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by

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ABSTRACT

SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY OF THE CHINLE FORMATION, SOUTHERN UTAH

By Christina M. Brown

The Upper Triassic Chinle Formation exposed in the Wolverine Petrified Wood area of the Grand Staircase-Escalante National Monument, southern Utah, preserves interbedded siltstone, sandstone, conglomerate, and paleosols representing a floodplain-dominated environment. Deposition was seasonal, and sediment was deposited episodically, allowing sufficient subaerial exposure for the deposits to undergo pedogenesis. Deposition was interrupted by four major and two minor periods of erosion resulting in the development of sequence boundaries. Fossils are rare and occur predominantly in the sandstone beds that overlie the sequence boundaries, indicating that sedimentation rates were high following erosional events. Petrographic and paleocurrent data suggest that the sediment source for most of the formation remained constant, and that the sediment was derived from the south and east. Paleosols changed from Vertisols, in the lower to middle part of the formation, to Aridisols near the top of the formation. This change is inferred to indicate an increasingly arid climate.

ACKNOWLEDGMENTS

In loving memory of Joseph Meisinger (1909-2000), Hazel Meisinger (1910-2002),

and Teresa Brown (1908-2003),

in grateful appreciation to Burtus and Dorothy Brown, and

in humble thanks to William and Sue Ann Brown

and field assistant and partner for life Peter Holland,

for their love and support.

I would also like to thank my thesis committee for their guidance and support: Calvin Stevens and David Andersen from San Jose State University and Phil Stoffer of the United States Geological Survey in Menlo Park.

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INTRODUCTION

The Chinle Formation consists of a series of siltstone, sandstone, and conglomerate beds and paleosols that extend across the Colorado Plateau (Fig. 1). Although this unit has been studied in detail in several areas, the depositional history in the Grand Staircase-Escalante National Monument has not been extensively studied or documented. Detailed geologic studies of the Chinle Formation near the Wolverine Petrified Wood Area of the Grand Staircase Escalante National Monument, where this study is located, were last conducted by Stewart et al. (1972a) as part of a regional study of the Colorado Plateau.

The purpose of this study is to determine the paleoenvironment, paleoclimate, and possible source areas for the Chinle Formation in order to determine how these changed over time, and to interpret the significance of periods of channeling and erosion. This was accomplished by measuring and studying stratigraphic sections; by making field observations of paleosols, sedimentary structures, and unit relationships; by studying thin sections of samples taken from key sandstone beds; and by identifying and interpreting the significance of fossils. The sections and descriptions were compared with those reported by other workers across the Colorado Plateau to establish correlations, clarify formational nomenclature, and compare paleoenvironmental interpretations.

This study adds to the stratigraphic understanding of the Chinle developed at other locations by previous workers by focusing on a previously undocumented area and by

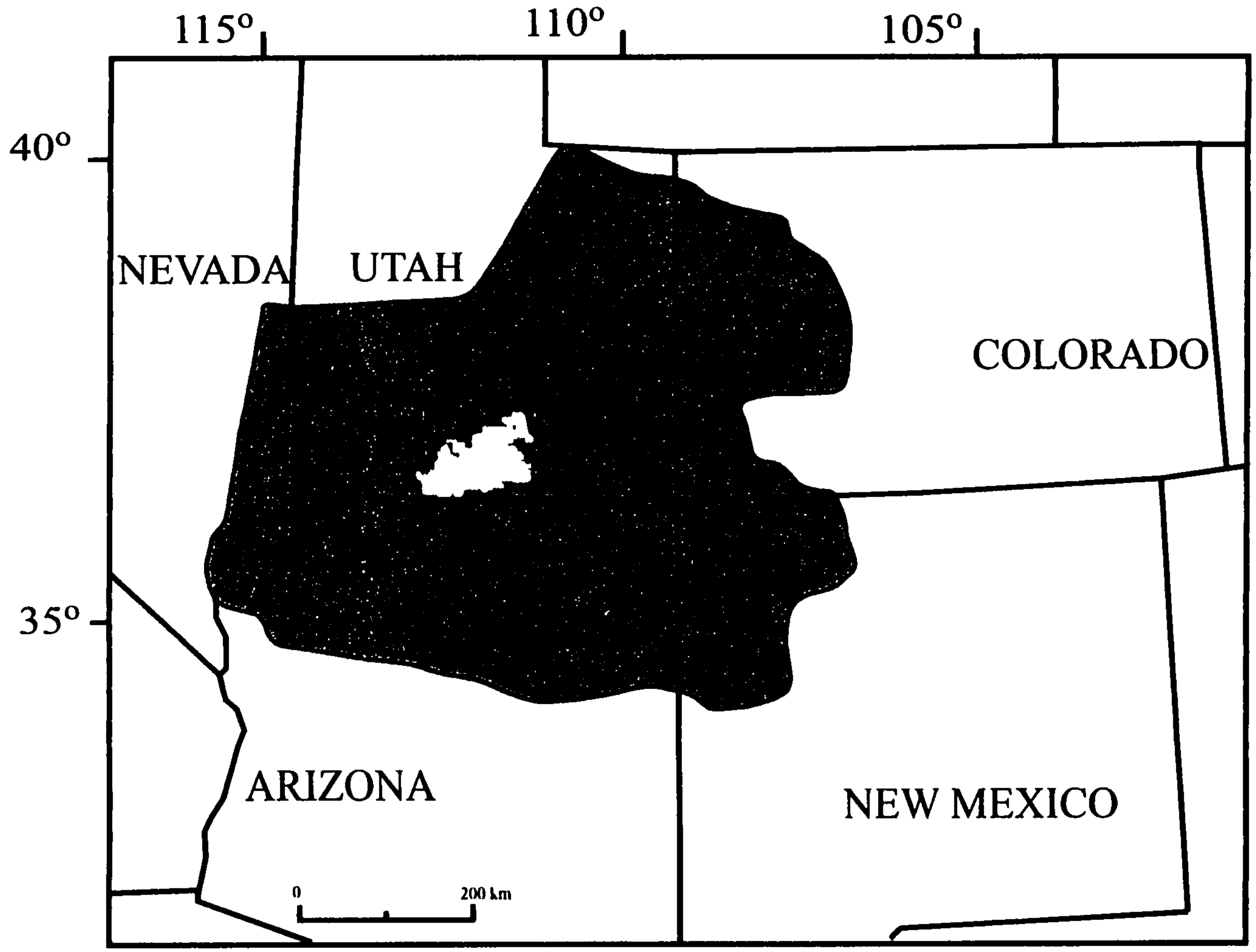


Figure 1. Distribution of Chinle Formation and related units (red-shaded area) across the Colorado Plateau (Grand Staircase-Escalente National Monument is shown in yellow) (adapted from Stewart et al., 1972a).

using a variety of methods in a single study in an attempt to gain a better understanding of the stratigraphy and depositional environment of the Chinle.

SETTING

Location of Study Area

The field area of this study is in the Wolverine Petrified Wood Area of the Grand Staircase-Escalante National Monument in southern Utah. The area is located about 52 km southeast of Boulder, Utah, in the Circle Cliffs, approximately 37° 47' N to 37° 49' N and approximately 111° 11' W to 111° 13' 30" W (Fig. 2).

Geomorphology

The study area is dominated by the cliff and bench topography that typifies the Grand Staircase-Escalante National Monument (Fig. 3). This topography is the result of erosion of sub-horizontally layered rocks. Variations in slope are defined by differences in rock type. In the field area, resistant sandstone beds form benches that are eroded by undercutting and collapse. Because of their resistant nature, these benches serve as temporary base levels for local erosional processes.

Several processes have shaped the geomorphology of the study area. Wetting and drying have had a large effect on the mudstones that make up much of the study area. The mudstones are rich in smectite clay, which expands when wet (Zuber and Parnell, 1989). Repeated wetting and drying gives the exposed mudstone slopes a distinctive appearance. When wet, the slopes bulge slightly outward. When the mudstones are completely dry, their convex shape is lost and their surface becomes very hard. The slope surface is covered with shallow cracks that reflect contraction of the soil as it dried after recent

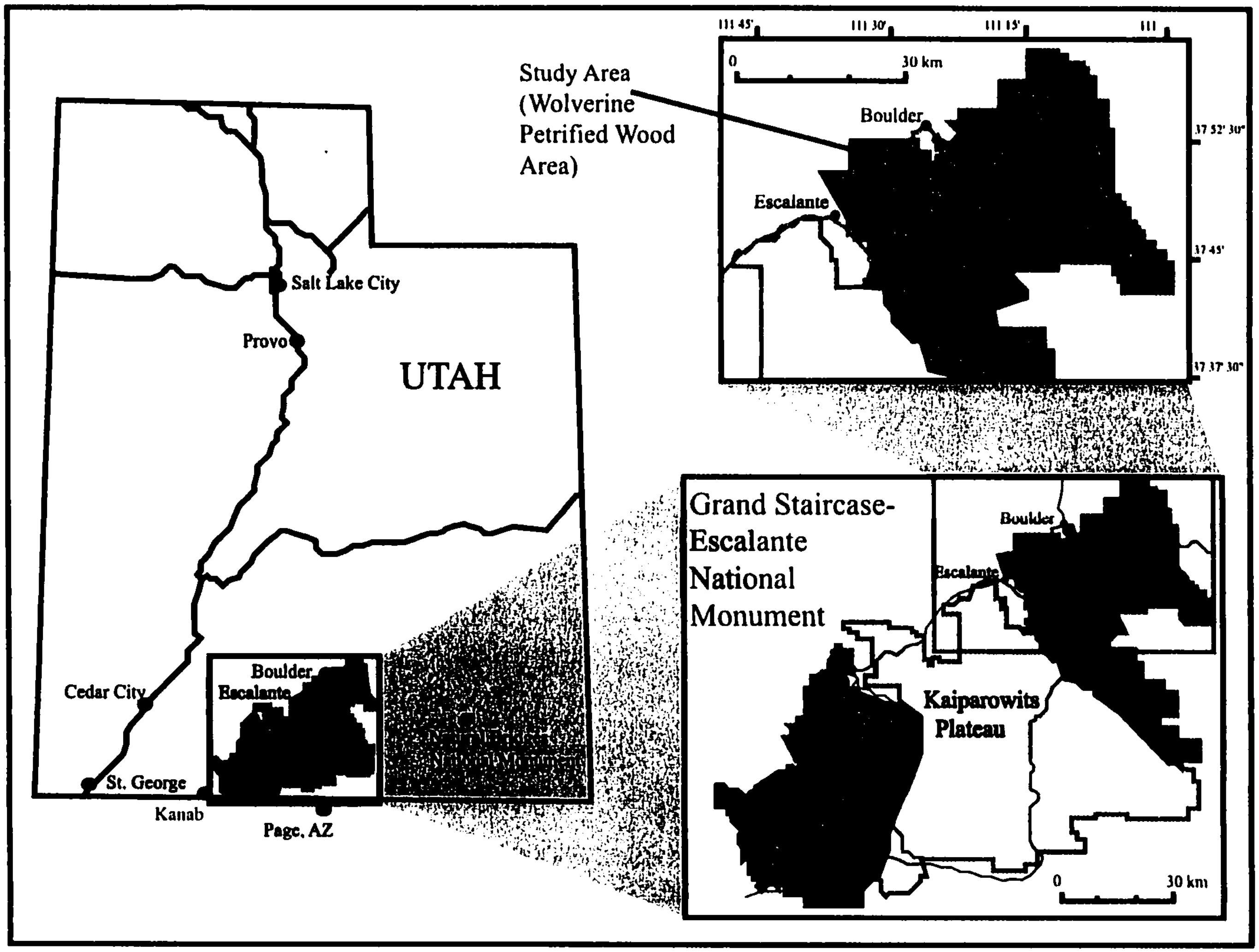


Figure 2. Location of study area.

Figure 3. Photo showing distinctive cliff and bench geomorphology of the study area. This photo was taken looking northwest from the road just east of the Wolverine Petrified Wood Area (Fig. 2). The nearest butte in the distance stands about 150 m tall.

precipitation. In addition, the surface typically is covered with a layer of whole and fractured carbonate nodules that have weathered out of the mudstone.

Freezing and thawing have had the greatest effect on the more resistant layers in the field area. This weathering process loosens sheets of rock along vertical fractures and dislodges them; this is typical of massive sandstone units such as the Wingate Formation (Easterbrook, 1993). Undercutting works with freezing and thawing to induce failure in the Wingate and in all other resistant units exposed in the field area. The Wingate Sandstone is particularly influential in shaping local morphology; collapsed pieces of the sandstone that fall onto the underlying slopes stabilize those slopes, give shelter to plants, and create environments favorable to the development of soil.

The high angle of the slopes in the upper members of the Chinle Formation makes access difficult. The best access is on those slopes stabilized by collapsed pieces of Wingate Sandstone, although those slopes commonly are obscured by the debris that stabilizes them.

Slumps also obscure exposures in the field area. The slopes of the buttes are susceptible to slumping because they are steep, covered with loosely consolidated material, and composed of clay-rich mudstone that swells when wet causing oversteepening (Easterbrook, 1993). Slumping is not always obvious; slump blocks are identified by the presence of transverse cracks and rotated or repeated beds. As a result of slumping, resistant facies of the Chinle Formation, which crop out on the surface of hills and buttes, commonly are broken and dip at various angles and in various directions.

Regional Depositional Setting

The Upper Triassic Chinle Formation, which occurs between the Lower to Middle Triassic Moenkopi Formation and the Jurassic Wingate Formation, was deposited in a subsiding continental basin (Fig. 4) on the western coast of Pangea (Stewart et al., 1972a; Dubiel, 1989a, 1991; Hasiotis and Dubiel, 1993; Dubiel and Hasiotis, 1994; Therrien and Fastovsky, 2000). Paleomagnetic data indicate that the Chinle depositional basin was located in the area between 5 and 15° north of the equator (Bazard and Butler, 1991; Hasiotis and Dubiel, 1993; Kent and Witte, 1993).

During the Triassic, the sea that lay to the west of the present Colorado Plateau regressed, creating an immense alluvial plain in this area. Rivers covered the lowlands of the Colorado Plateau with moderately thick deposits of silt, mud, and sand now represented by the Chinle Formation and the continental facies of the Moenkopi Formation (Hasiotis and Dubiel, 1993).

Deposition of the Chinle Formation was centered near what is now the four corners area of Colorado, Utah, New Mexico, and Arizona (Fig. 1). Previous paleocurrent measurements have indicated that sediment was derived from two major mountain belts (Fig. 5), the Ancestral Uncompahgre Highlands/Ancestral Rocky Mountains to the east and the Mogollon Highlands to the south (Stewart et al., 1972a; Blakey and Gubitosa, 1983; Dubiel and Hasiotis, 1994; Therrien et al., 1999).

The Chinle Formation filled three paleovalleys, all of which extend roughly northwest-southeast across the Colorado Plateau (Fig. 5). These valleys are (from southwest to northeast) the Vermillion Cliffs paleovalley, the Painted Desert paleovalley,

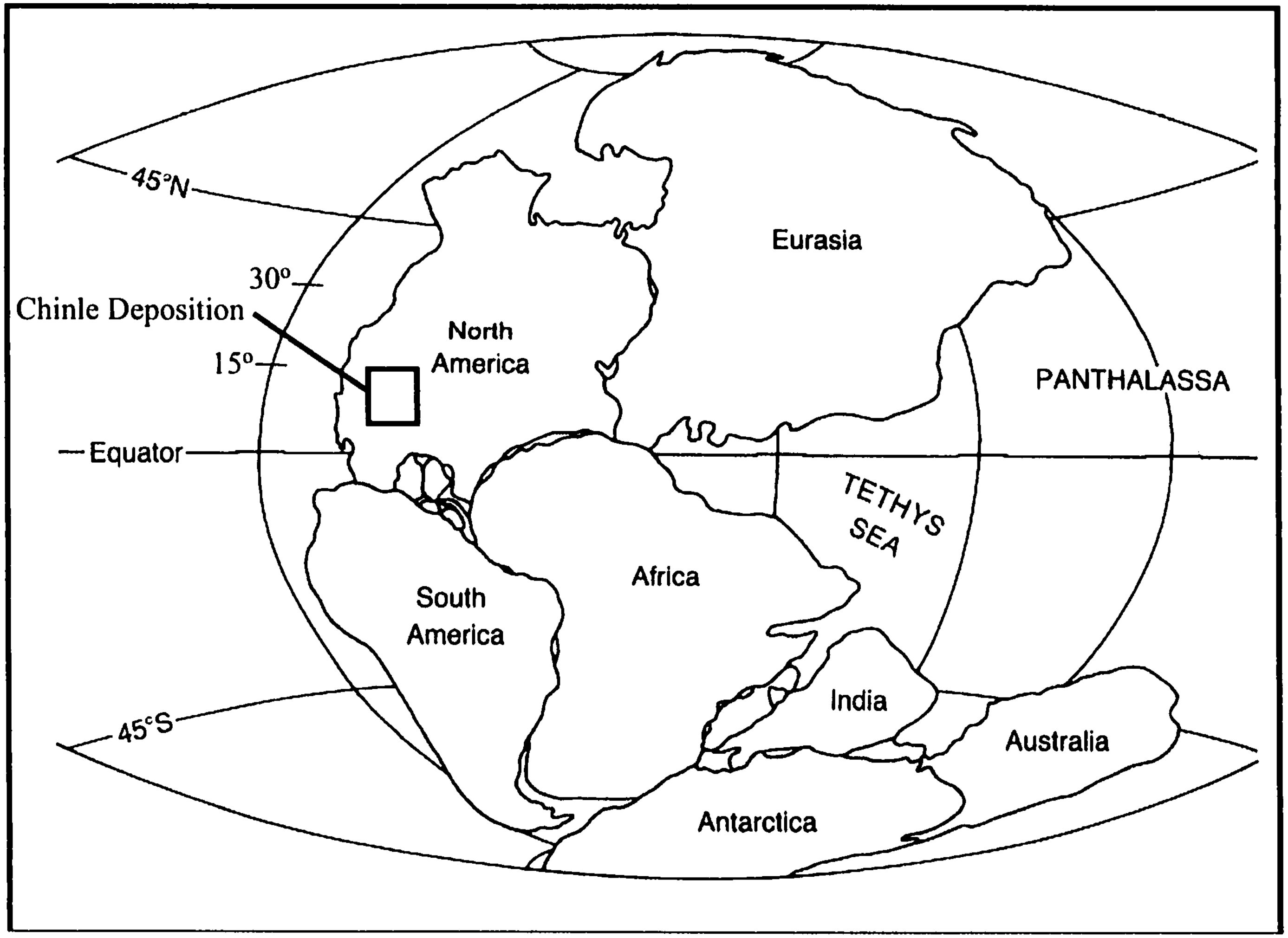


Figure 4. Location of Chinle Formation on Pangea at 220 Ma (adapted from Cooper et al., 1990).

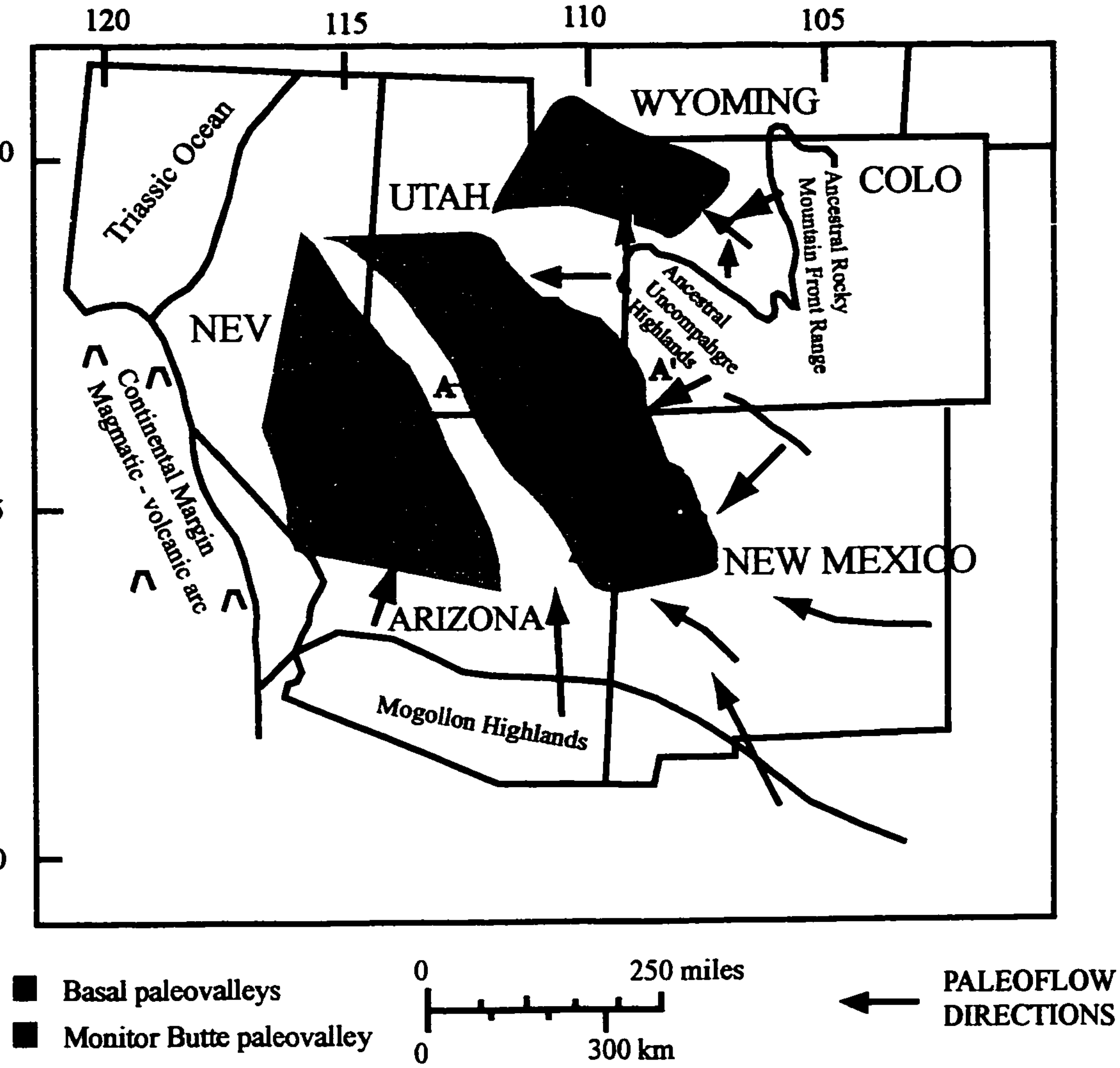


Figure 5. General directions of clastic sediment transport into the Chinle paleovalley systems. ES is the Eagle System, PDS is the Painted Desert System, and VCS is the Vermillion Cliffs System (adapted from Blakey and Gubitosa, 1984; Dubiel, 1991; Demko, 1995; and Dubiel et al., 1999). Cross-section A to A' is illustrated in Figure 6.

and the Eagle paleovalley (Demko, 1995). All three paleovalleys are cut into the underlying Moenkopi Formation, partially removing it by erosion; in some areas in the easternmost exposures of the Chinle, the Moenkopi has been eroded away entirely so that the Chinle rests directly on Permian and older rocks (Demko, 1995). The study area is in the Painted Desert paleovalley (Fig. 5).

These paleovalleys are as much as 120 m deep and 150 km wide; local scours in the paleovalleys extend an additional 90 m in depth and are up to 8 km in width (Demko, 1995). The basal member of the Chinle Formation (Fig. 6) represents the initial infilling of these paleovalleys (Demko, 1995). After deposition of this basal member, a second erosional event occurred creating the Monitor Butte paleovalley within the Painted Desert paleovalley; the Monitor Butte paleovalley was filled by the middle to upper parts of the Chinle Formation (Demko, 1995; Demko et al., 1998).

The Chinle Formation records two episodes of volcanic activity (Stewart et al., 1972a; Sigleo, 1978a,b; Blakey and Gubitosa, 1983; Stewart et al., 1986; Harris et al., 1997). The first occurred during deposition of the lower part of the Chinle Formation, during the Carnian (early Late Triassic) (Blakey and Gubitosa, 1983; Stewart et al., 1986). The location of the volcanic activity is unknown except that it was south of the Chinle depositional basin (Stewart et al., 1986). Some workers (Blakey and Gubitosa, 1983) have suggested that the Mogollon Highlands were the source of the volcanics, but U-Pb dating indicates that the igneous rocks in the Mogollon Highlands are at least 25 m.y. too young (Stewart et al., 1986).

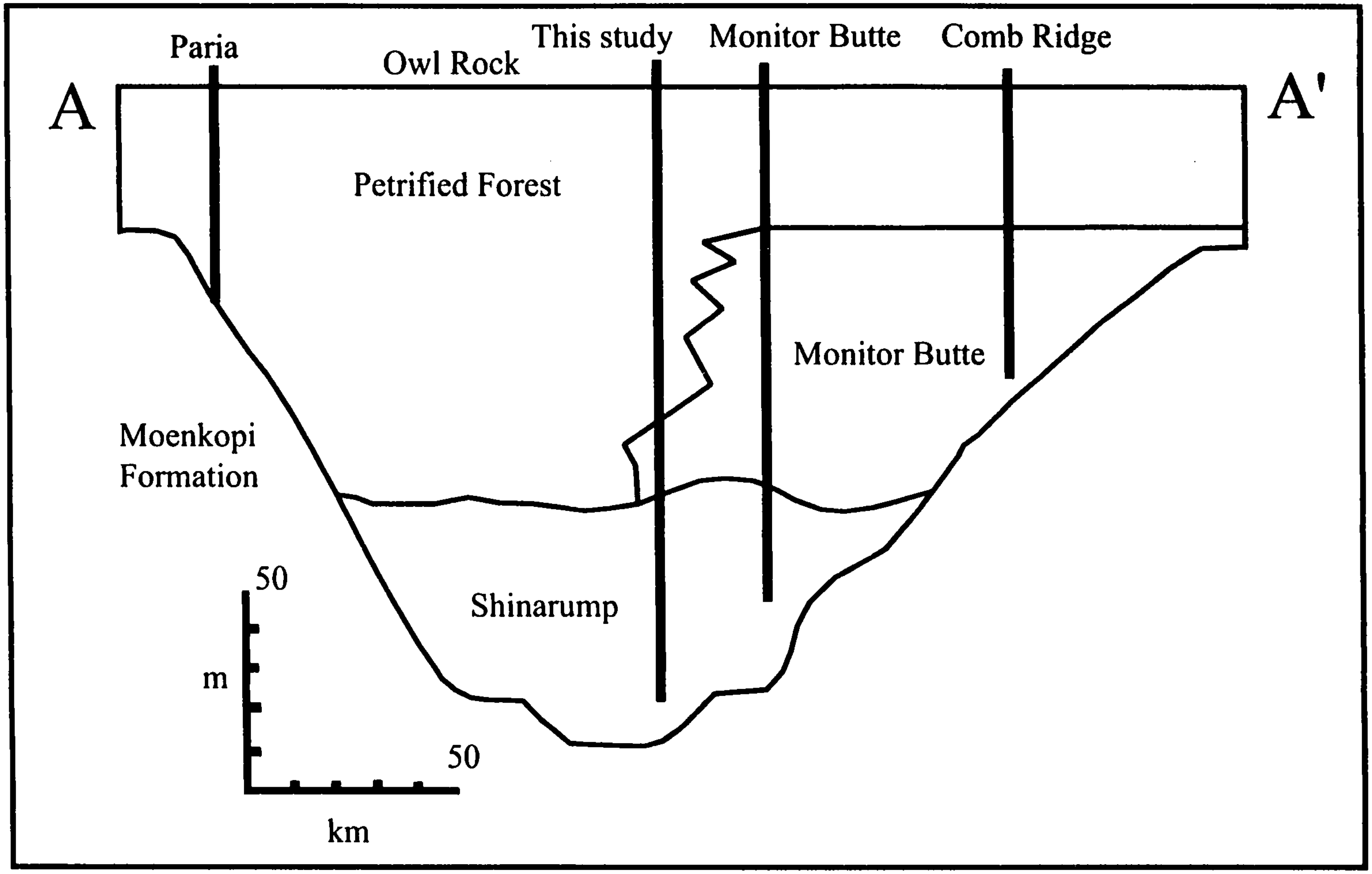


Figure 6. Cross-section showing major members of the Chinle Formation in the Painted Desert paleovalley (adapted from Dubiel, 1991; Demko, 1995; and Dubiel et al. 1999); for location see Figure 5.

The second episode of volcanism occurred at the end of the Triassic, near the end of Chinle deposition (Stewart et al., 1972a; Sigleo, 1978a,b; Harris et al., 1997). A chain of volcanoes to the west (Harris et al., 1997) and an unknown volcanic source to the south (Stewart et al., 1972a; Sigleo, 1978a,b) erupted large amounts of ash and volcanic debris. Winds and streams carried volcanic material northward and eastward from these sources into the Chinle basin (Harris et al., 1997).

PREVIOUS INVESTIGATIONS

Geologic exploration of the Colorado Plateau began in 1853 with the work of Jules Marcou (1855) who recognized a unit he called the New Red Sandstone, a unit corresponding to rocks now known as part of the Moenkopi and Chinle formations.

Marcou was followed by Newberry (1861) who explored northern Arizona, northwestern New Mexico, southwestern Colorado, and southwestern Utah over the course of two expeditions. The first was the Ives expedition in 1857 and the second was the Macomb expedition in 1858.

From the 1860's through the 1880's, the Colorado Plateau was evaluated by four major surveys. These were the Wheeler, Hayden, King, and Powell surveys. It was during the Powell survey of 1876 that the first modern nomenclature was used. Powell (1876) used "Shinarump Group" to name beds now referred to as the Moenkopi and Chinle formations.

In 1916, 1917, and 1918 Gregory led a series of expeditions into the Plateau. Gregory added to the modern nomenclature, redefining the Shinarump Conglomerate and naming the Chinle Formation. He subdivided the Chinle into four units, referred to as units A, B, C, and D (Gregory, 1917). Although no longer referred to by these letters, these divisions define units that are still recognized as members of the Chinle Formation.

From the 1920's to the 1960's, work was carried out on the Colorado Plateau by a variety of workers, mostly under the direction of the United States Geological Survey. Of special note is the paper by Maxey (1946), which was the first to refer to the Petrified Forest Member, a unit redefined to its current definition by Gregory and Williams (1947).

Stewart (1961) published a series of stratigraphic columns measured at locations across the Colorado Plateau as part of a study to understand the regional stratigraphy and origin of the Chinle Formation. Two of his columns were located close to the study area of this investigation, in the Horse Canyon and Silver Falls Creek areas.

Recently, the stratigraphy of the Chinle Formation has been studied in many areas, most exhaustively in Petrified Forest National Park, Arizona, by workers including Hasiotis and Dubiel (1993), Demko (1995), and Harris et al. (1997). Exposures in New Mexico have been studied by Robertson (1981) and Dubiel (1989a, b); Zion Park in Utah was investigated by Gregory (1950).

Paleosols in the Chinle have been studied by a variety of workers (Kraus and Middleton, 1987; Zuber and Parnell, 1989; Dubiel and Hasiotis, 1994; Therrien and Fastovsky, 2000). Therrien et al. (1999) identified paleosols at three locations in Petrified Forest National Park (PFNP), Arizona, and Dubiel and Hasiotis (1994) have studied paleosols in PFNP, in the Canyonlands of Utah, and in the Eagle Basin of Colorado.

The fossils of the Chinle Formation have been studied by a variety of workers including Ash (1974, 1975, 1976, 1978) and Hasiotis et al. (1998). Fossils common in the Chinle include carbonized trees, carbonized leaves, permineralized trees, and trace fossils, all indicating a largely continental environmental setting.

Recent research into the climate and environment at the time of deposition has been conducted by numerous workers including Blakey and Gubitosa (1984), Dubiel

(1989a, 1989b, 1991), Lucas (1993, 1994), Dubiel and Hasiotis (1994), Demko (1995), Heckert (1995), and Harris et al. (1997). These investigations used stratigraphic, lithologic, and taphonomic data for interpreting the depositional environments.

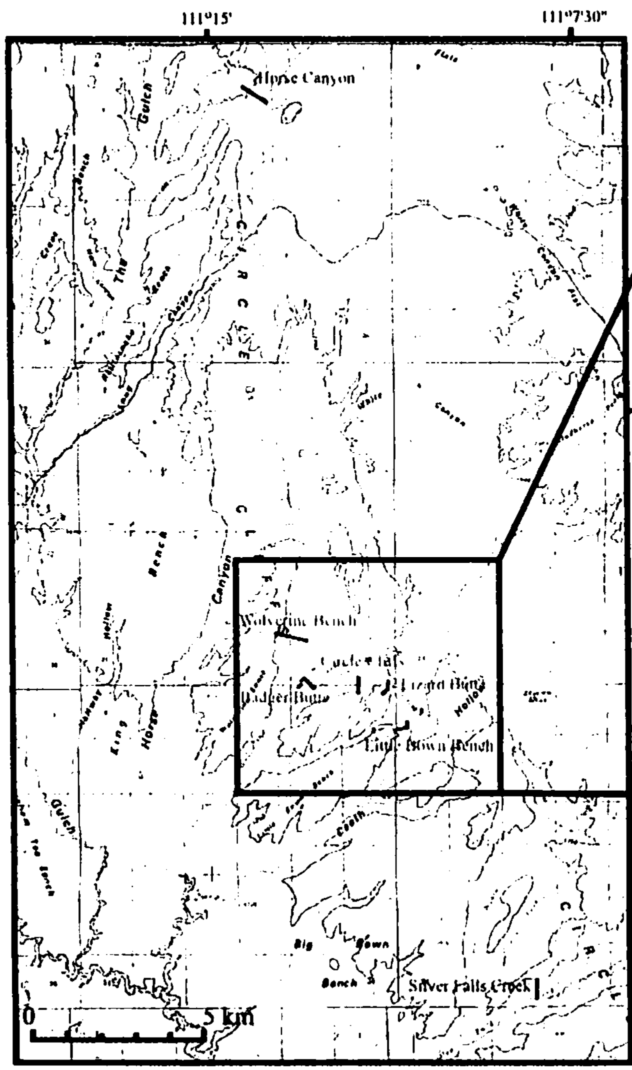
METHODS

Data for this study were collected from field and laboratory analyses. Twenty-two days were spent in the field, during which observations were made and samples collected for laboratory analysis. Laboratory analysis consisted of thin-section study of sandstones.

Field Methods

Fieldwork centered on the description of sedimentary facies and their relationships to one another. To accomplish this, five stratigraphic sections were measured using a Jacob's staff and a Brunton compass. The sections were measured along the flanks of Wolverine Bench, a butte immediately east of Wolverine Bench referred to as Badger Butte in this study, a bench immediately east of Badger Butte referred to as Circle Cliffs in this study, a butte immediately east of Circle Cliffs referred to as Lizard Butte in this study, and Little Bown Bench (Fig. 7). As sections were measured, descriptions of lithofacies, sedimentary structures, and facies geometry and architecture were recorded. Plant and animal fossils were described, their locations noted, and, in the cases of plant fossils, samples collected for laboratory analysis. The orientation and inclination of logs in the primary log-bearing unit as well as the direction in which their root balls lay were measured.

The stratigraphic nomenclature employed for the Chinle Formation in different areas across the Colorado Plateau is compared to the units recognized in this study in Figure 8. Units were identified and assigned names based on the descriptions and



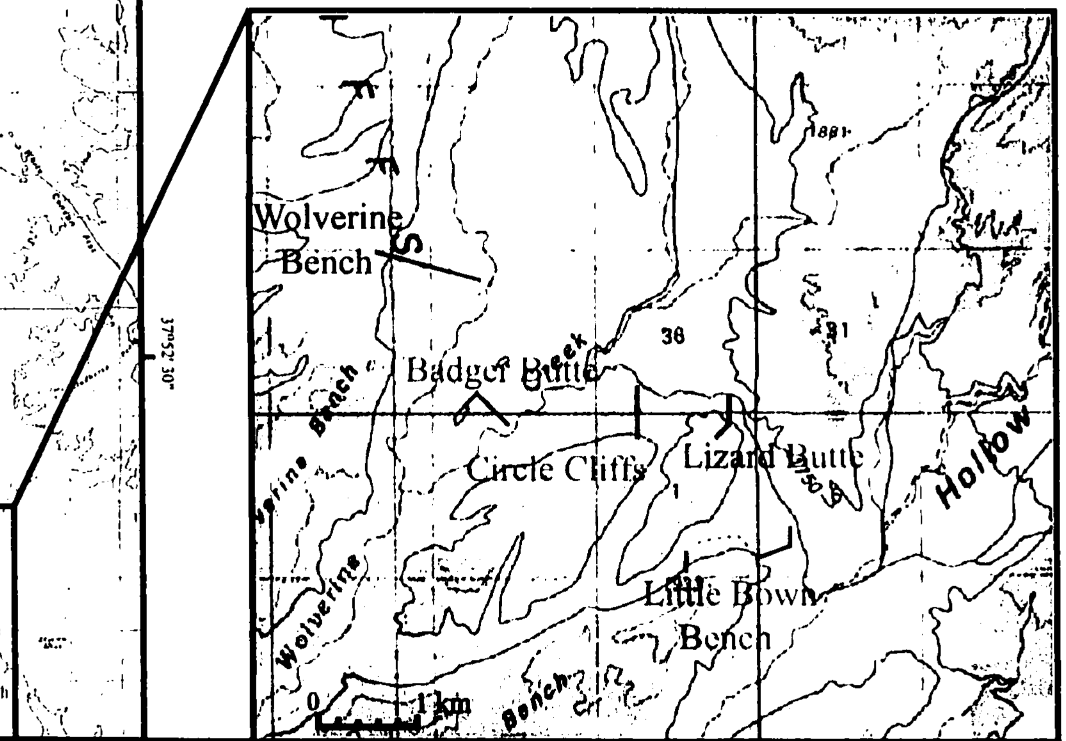


Figure 7. Locations of the traverses along which stratigraphic sections have been measured. Stewart's (1961) sections are named and shown in blue (left). Sections measured for this study are named and shown in red (left and above). Map to the left is from Escalante 1:100,000 scale map (USGS, 1980) and the above map is from Pioneer Mesa 7.5-Minute Quadrangle (USGS, 1987).

conventions of Stewart (1961), Stewart et al. (1972a), Lucas (1991, 1993, 1994), and Lucas et al. (1997a, 1997b).

Identification and interpretation of sedimentary structures was based on the descriptions and interpretations given by Compton (1985) and Pettijohn et al. (1987). Cross-bedding is divided into two major types, planar and trough (Pettijohn et al., 1987). Planar cross-beds are further divided into tabular-planar and wedge-planar depending on the orientation of their truncation surfaces (Compton, 1985; Pettijohn et al., 1987). Trough cross-beds have curved truncation surfaces (Compton, 1985). The shape of forsets between truncation surfaces is described as angular, parabolic (tangential), or sinusoidal (Compton, 1985). The orientation of the cross-beds was used, where discernable, for paleocurrent measurements.

Classification and interpretation of stratigraphic relationships was based on the descriptions and interpretations given by Pettijohn et al. (1987) and Miall (1996).

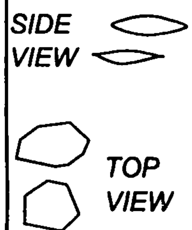
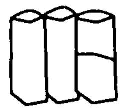
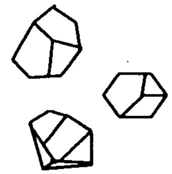
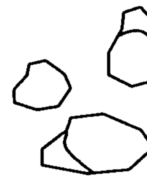
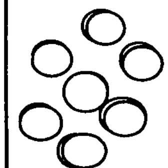
Interpretation of mudstones as paleosols was based on evidence of former roots, presence of recognizable soil horizons, and preservation of relict soil structures such as peds and nodules (Table 1). Once recognized as paleosols, mudstones were classified using the system developed by Retallack (2001) (Table 2).

Two stratigraphic sections measured by Stewart (1961) in the Horse Canyon and Silver Falls Creek areas (Fig. 7) were also studied. Lithofacies, sedimentary structures, and facies geometry and architecture were again described with special emphasis on the identification of stratigraphic units. This was done to establish correlation with Stewart's work.

Table 1: Descriptive shorthand for identification of soil and paleosol horizons (adapted from Retallack, 2001).

Category	***Term***	***Description***
Master horizons	O	Surface accumulation of organic matter (peat, lignite, coal) overlying clayey or sandy part of soil
	A	Accumulation of humified organic matter mixed with mineral fraction. Occurs at the surface or below an O horizon.
	E	Underlies an O or A horizon and is characterized by less organic matter, less sesquioxides (Fe2O3) and Al2O3), or less clay than the underlying horizon. This horizon is usually light colored as a result of abundant quartz.
	B	Underlies an O, A, or E horizon and shows discernible enrichment in clay, carbonate, sesquioxides (Fe2O3 and Al2O3) or organic matter
	K	Subsurface horizon so impregnated with carbonate that it forms a massive layer
	C	Subsurface horizon more weathered than bedrock but lacking degree of weathering of A, E, B, and K horizons
	R	Consolidated and unweathered bedrock
Gradations between master horizons	AB	Horizon with some characteristics of A and of B, but with A characteristics dominant
	BA	Horizon with some characteristics of A and of B, but with B characteristics dominant
	E/B	A horizon, predominantly like B horizon but with tongues of E horizon
Subordinate divisions	c	Concentration of materials/minerals or formation of nodules
	k	Accumulation of carbonates less than for K
	n	Accumulation of halite, columnar peds
	q	Accumulation of silica
	s	Illuvial accumulation of sesquioxides
	t	Accumulation of clay

Table 2: Classification of soil peds (adapted from Retallack, 2001).

TYPE	PLATY	COLUMNAR	ANGULAR BLOCKY	SUBANGULAR BLOCKY	GRANULAR
SKETCH					
DESCRIPTION	tabular and horizontal to land surface	elongate with domed top and vertical to surface	equant with sharp interlocking edges	equant with dull interlocking edges	spheroidal with slightly interlocking edges
USUAL HORIZON	E, Bs, K, C	Bn	Bt	Bt	A
MAIN LIKELY CAUSES	initial disruption of relict bedding; accretion of cementing material	erosion by percolating water, and swelling of clay	cracking around roots and burrows; shrinking and swelling on wetting and drying	as for angular blocky, but with more erosion and deposition of material in cracks	active bioturbation and coating of soil with films of clay, sesquioxides, and organic matter
SIZE CLASS	very thin < 1mm	very fine < 1cm	very fine < .5cm	very fine < .5cm	very fine < 1mm
	thin 1 to 2 mm	fine 1 to 2 cm	fine .5 to 1 cm	fine .5 to 1 cm	fine 1 to 2 mm
	medium 2 to 5 mm	medium 2 to 5 cm	medium 1 to 2 cm	medium 1 to 2 cm	medium 2 to 5 mm
	thick 5 to 10 mm	coarse 5 to 10 cm	coarse 2 to 5 cm	coarse 2 to 5 cm	coarse 5 to 10 mm
	very thick > 10 mm	very coarse >10cm	very coarse >5cm	very coarse >5cm	very coarse >10mm

Paleocurrent Calculations

Using GEOrient (Holcombe, 2000), log orientation and paleocurrent data were plotted on frequency-azimuth rose diagrams using direction lines. Vector mean and circular standard deviation were also calculated in GEOrient (Holcombe, 2000). Vector strength was also calculated (Curray, 1956).

Petrographic Analysis

Twenty samples of relatively unweathered sandstone were collected for petrographic analysis; one sample was taken from each of four distinctive marker beds in each of the five measured stratigraphic sections. Samples were analyzed in order to discern whether or not they reflect different sources.

Of the 20 sandstone samples, 16 were analyzed and point counted using the Gazzi-Dickinson method (Dickinson, 1970) except that authigenic material also was counted. The authigenic material was not included in the totals used to classify the rocks, however, but was instead used to gain knowledge of its relative abundance from sample to sample and to interpret the origin of diagenetic constituents. Between 100 and 120 points were counted on each thin section using a measured millimeter grid.

STRATIGRAPHY AND SEDIMENTOLOGY

Moenkopi Formation

The Lower to Middle Triassic Moenkopi Formation lies directly below the Chinle Formation. According to Stewart et al. (1972b), the Moenkopi was named in 1901 by L.F. Ward for a section in Moenkopi Wash in north-central Arizona. The Moenkopi is not exposed in the study area, although it is well exposed north of the study area where it contains brick-red, horizontally bedded mudstones.

Chinle Formation

The Chinle Formation was named by Gregory (1917) for exposures in Chinle Valley located in northeastern Arizona. The Upper Triassic Chinle Formation unconformably overlies the Moenkopi Formation and the basal member of the Chinle partially fills channels cut into the Moenkopi (Demko, 1995).

A complex nomenclature has been used to describe Triassic rocks across the Colorado Plateau, and the Chinle has been subdivided in various ways. Relatively recently, Lucas (1994) and Lucas et al. (1997) suggested that the units within the Chinle should be raised to formational status. By his definition, all Upper Triassic, non-marine strata in the western United States belong to the Chinle Group. The reasoning behind his departure from the traditional hierarchy, which places the Chinle as a formation, was to emphasize the "lithostratigraphic integrity" of the subdivisions (Lucas, 1994; Lucas et al., 1997).

In this study, however, because the subdivisions of Chinle are too thin to be mappable at a scale of 1:24,000, the Chinle is considered to be a formation. In keeping with this decision, the Shinarump, Monitor Butte, Bluewater Creek, Petrified Forest, and Owl Rock formations of Lucas are here considered to be members (Fig. 8). The units recognized by Lucas et al. (1997b) within the Shinarump, the Mottled Strata and Shinarump, will be referred to as submembers in this study. The three units recognized by Lucas (1994) and Lucas et al. (1997) within the Petrified Forest unit, the Lower Petrified Forest, the Moss Back, and the Upper Petrified Forest, will be called submembers in this study. The uppermost unit of the Chinle Formation is referred to in this study as the Church Rock Member in keeping with the terminology of Stewart et al. (1972). The Church Rock Member is laterally equivalent to the Rock Point Member (Lucas et al., 1997).

For this study, sedimentology of the Chinle Formation and the stratigraphic relationships between its members were studied and described during the measurement of five measured sections in the field area (Fig. 7). The descriptions and measurements are contained in the Appendix and the sections are shown graphically in Figure 9. A composite stratigraphic column was created using thicknesses and descriptions averaged from all five stratigraphic sections; this column is shown in Figure 10 and summarizes the stratigraphic sequence seen in the study area. The typical physical appearance and relationship of some of the units in the study area is shown in Figure 11.

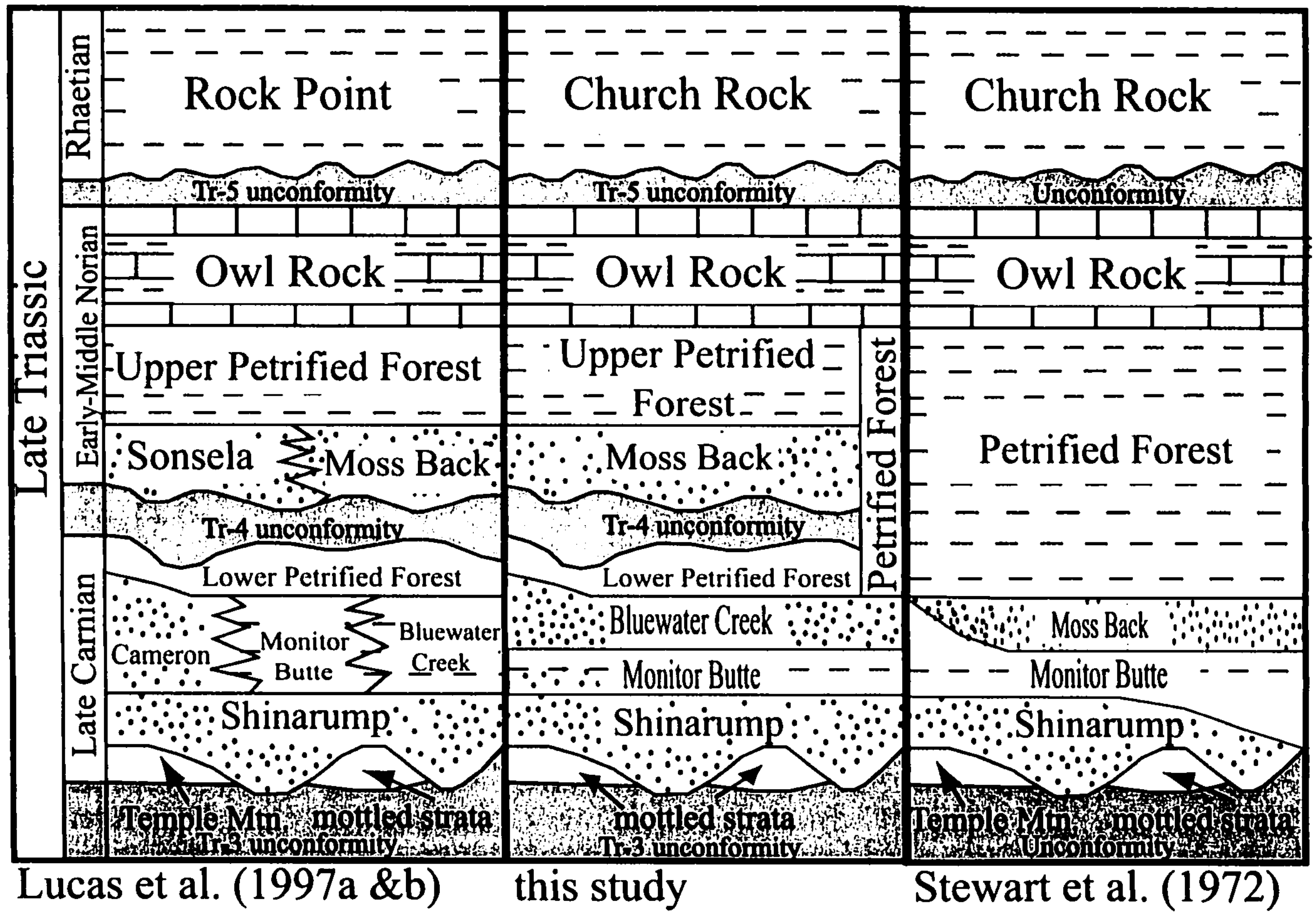


Figure 8. Summary of nomenclature used for the Chinle Formation and associated units in northeast Arizona and southeast Utah.

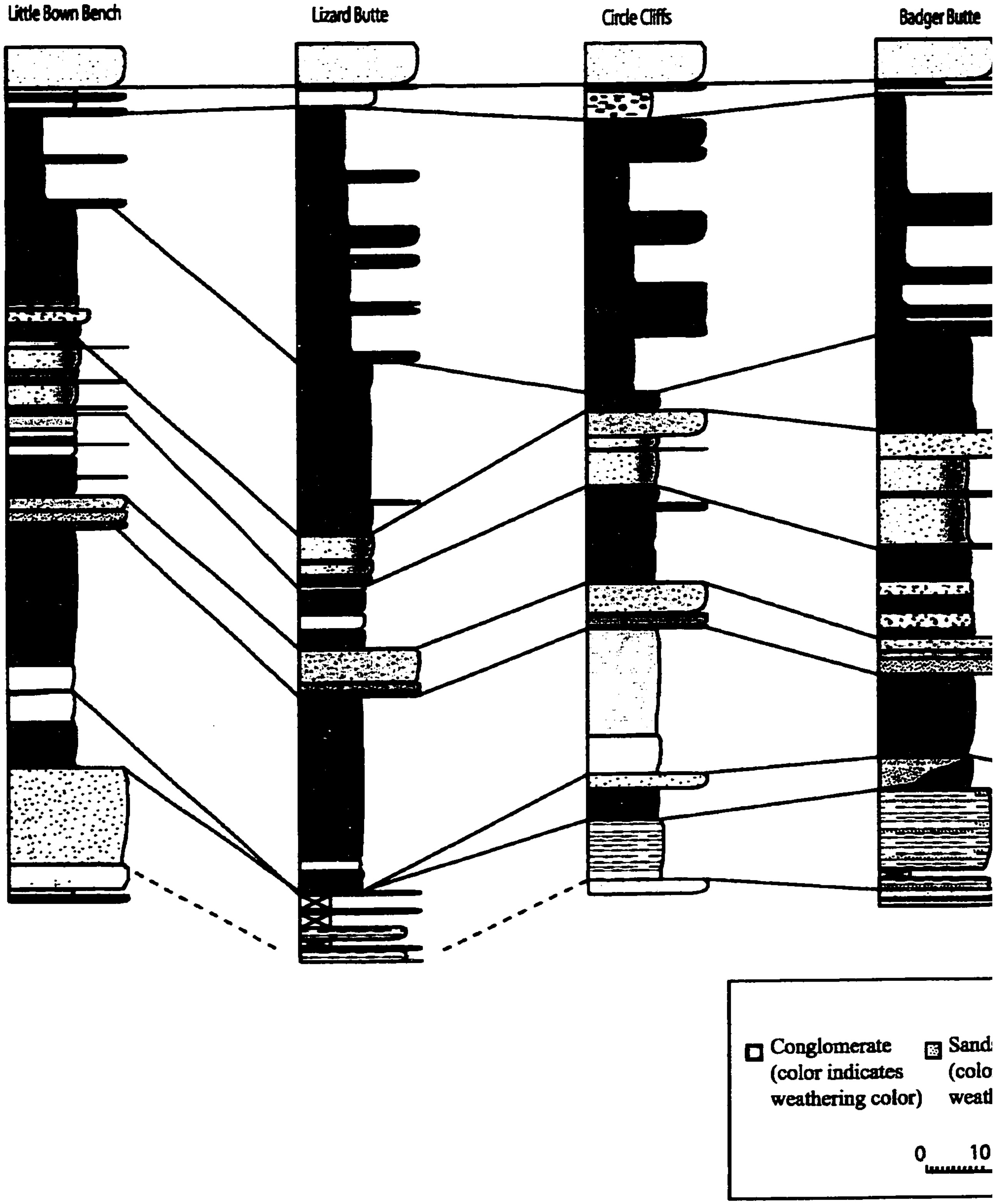
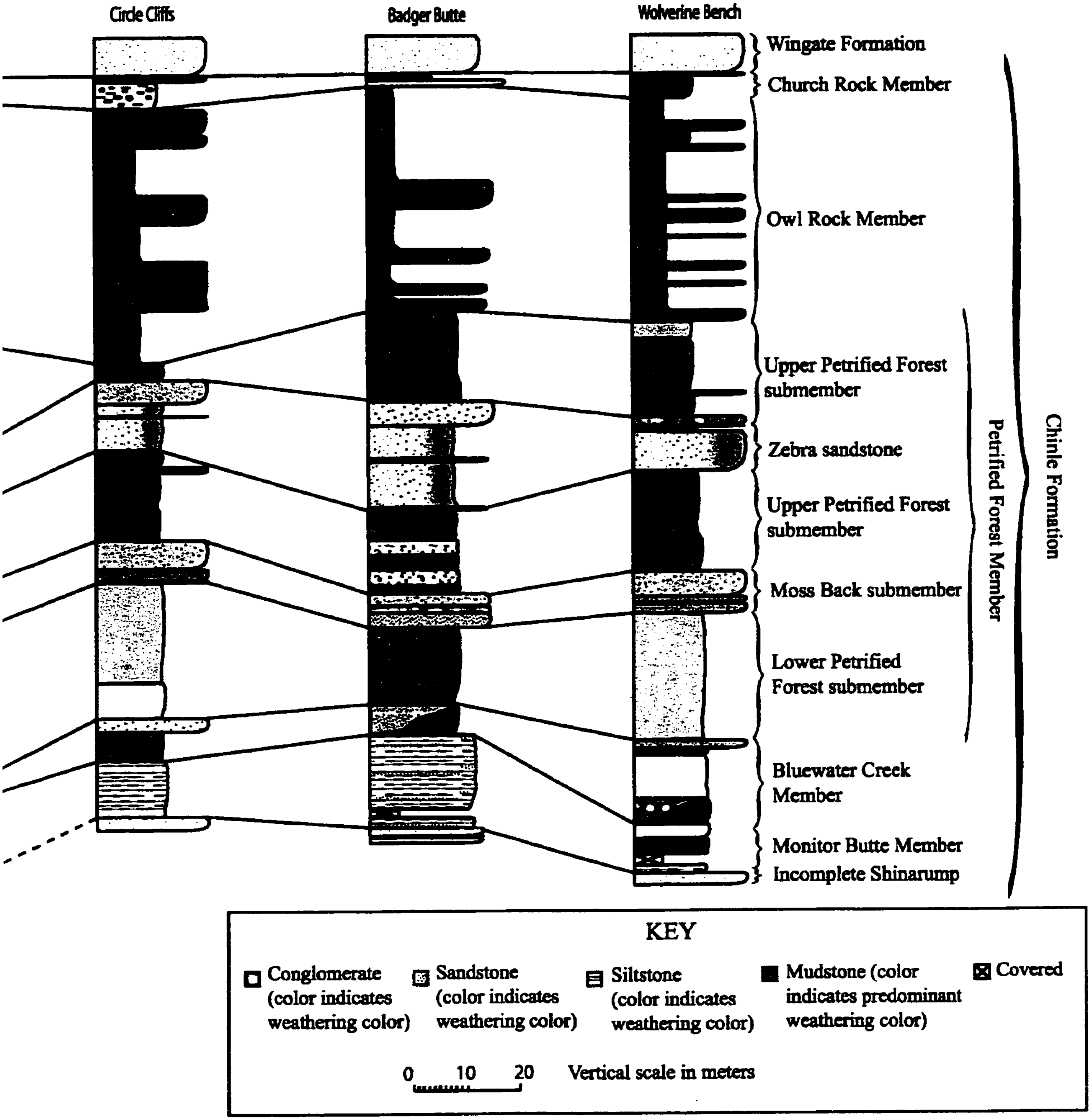
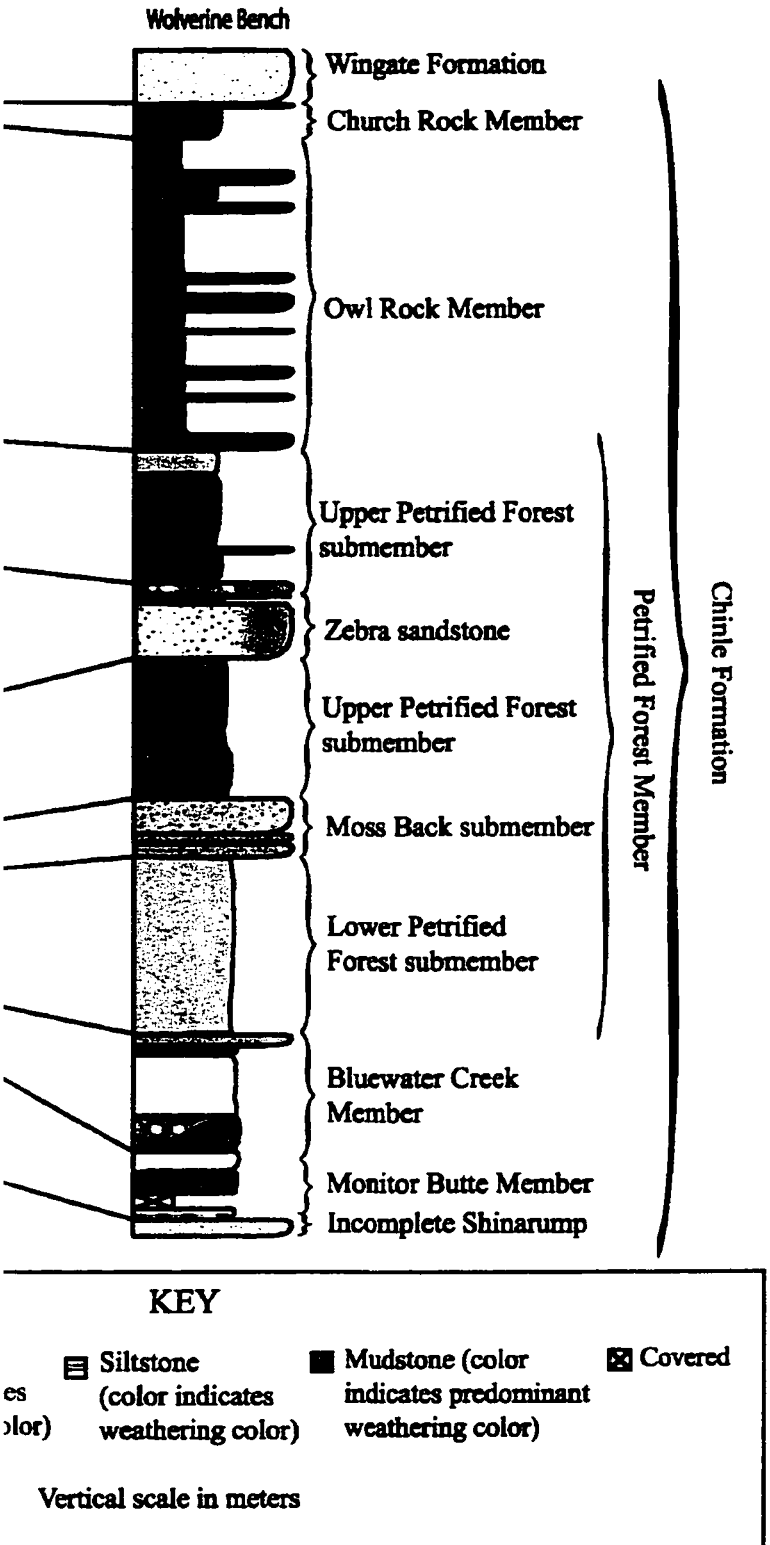


Figure 9. Correlation of measured stratigraphic sections in this study.



stratigraphic sections in this study.


Wolverine Bench
Wingate Formation
Church Rock Member
Owl Rock Member
Upper Petrified Forest submember
Zebra sandstone
Upper Petrified Forest submember
Moss Back submember
Lower Petrified Forest submember
Bluewater Creek Member
Monitor Butte Member
Incomplete Shinarump
Petrified Forest Member
Chinle Formation
KEY
es
lor)
Siltstone (color indicates weathering color)
Mudstone (color indicates predominant weathering color)
Covered
Vertical scale in meters

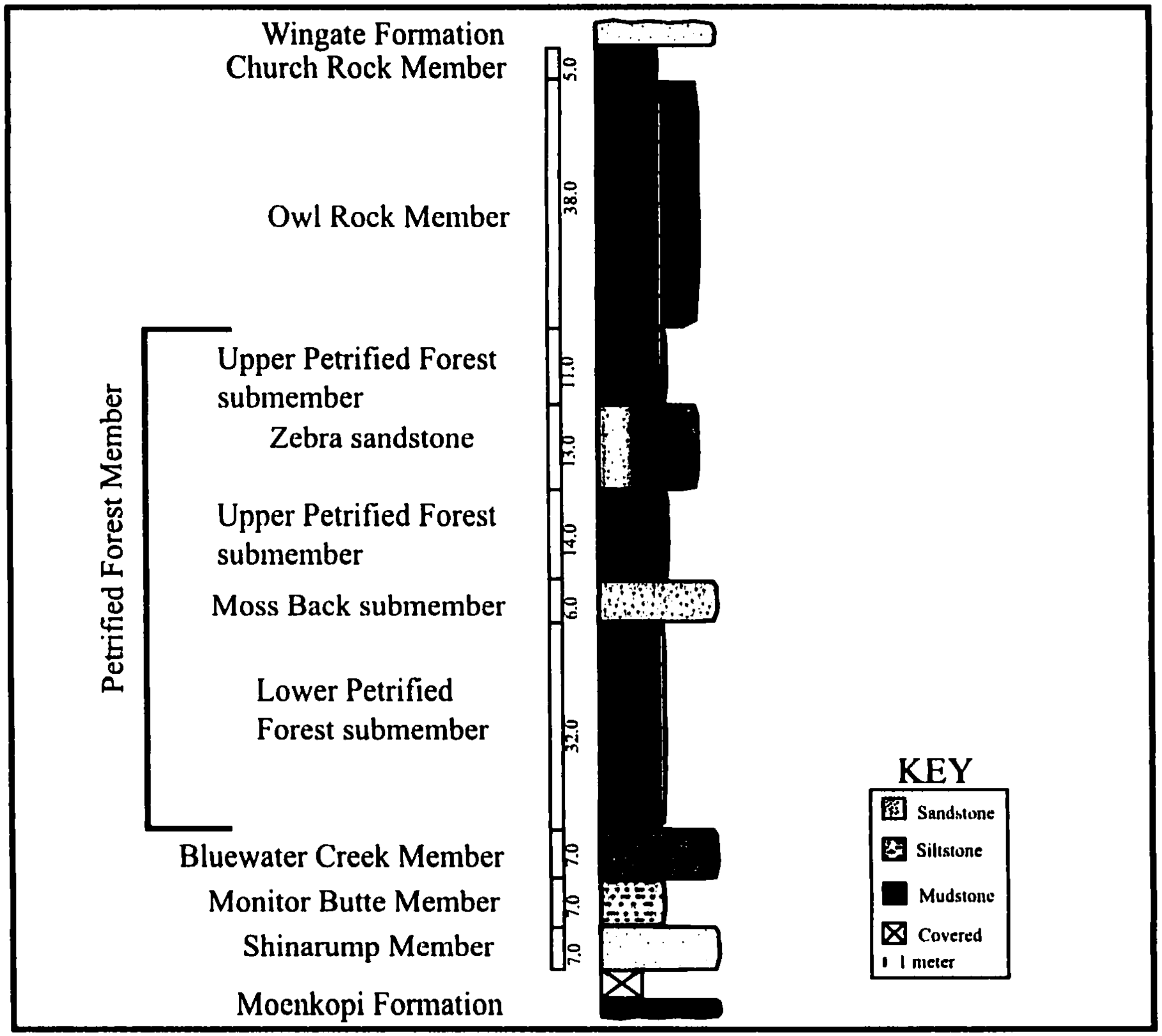


Figure 10. Composite stratigraphic column for field area. In all units, color indicates predominant weathering color and numbers refer to thicknesses in meters.

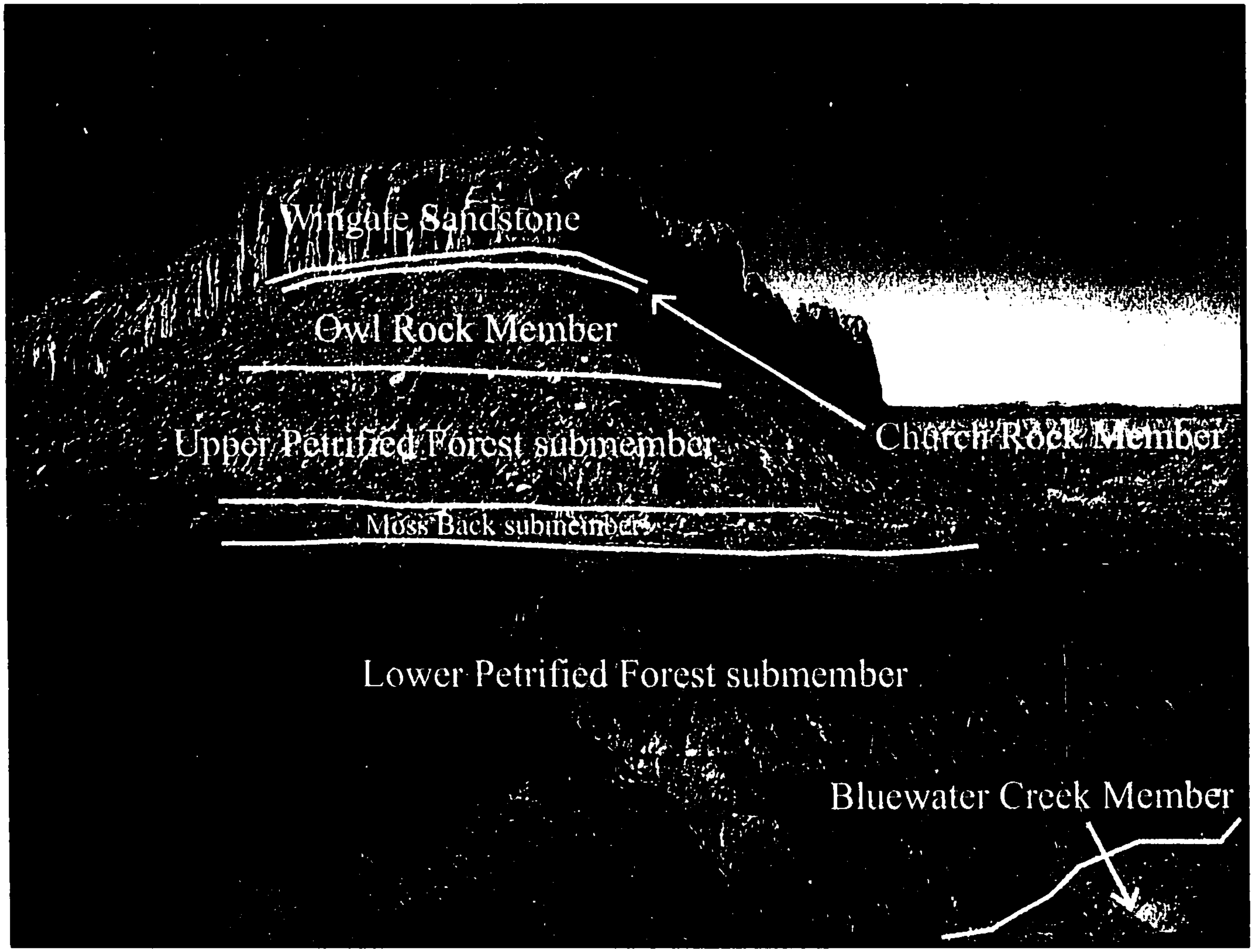


Figure 11. Some of the stratigraphic units in the study area as exposed on the flank of the Circle Cliffs.

Shinarump Member

The Shinarump Member was named for the Shinarump Cliffs in southwestern Utah by Powell (1876). It can be subdivided into the Mottled Strata submember, the Temple Mountain submember, and the Shinarump submember (Dubiel, 1991). The Mottled Strata submember is made up of massive, biologically and pedogenically altered mudstone, sandstone, and conglomerate (Lucas et al., 1997a) and has a distinctive mottled appearance (Lucas et al., 1997b). The Temple Mountain submember occurs only in the San Rafael Swell of east-central Utah and is equivalent to the Mottled Strata submember. The two submembers commonly have a similar appearance except that original bedding is commonly preserved in the Temple Mountain submember (Lucas et al., 1997a). The Shinarump submember is a predominantly yellowish-gray, cross-bedded quartzarenite and conglomerate unit (Lucas et al., 1997b).

The contact between the Shinarump Member and the underlying Moenkopi Formation is erosional. The Shinarump Member fills channels cut into the Moenkopi resulting in a greatly variable thickness for the Shinarump Member from place to place (Heckert and Lucas, 1996).

In the study area, two submembers of the Shinarump Member are exposed, the Mottled Strata submember and the Shinarump submember. The basal Mottled Strata submember, which crops out only in the Little Bown Bench area, is composed of mudstone that is red with green mottles (Appendix) on both weathered and fresh surfaces. The Shinarump submember generally is composed of fine- to coarse-grained sandstone with lenses of pebbly sandstone and conglomerate. The sandstone commonly has 1-mm-thick laminations of alternating red and white sandstone or hematite staining on weathered surfaces. On fresh surfaces, these rocks are light green with 1-mm-diameter, round, red mottles. This submember is resistant and forms cliffs, especially along active stream channels.

Because it is exposed in modern stream channels, the amount of Shinarump Member exposed differs from place to place throughout the study area, and the base of the Shinarump Member remains covered. In the Lizard Butte area, the whole member is covered. Where it is exposed, the incomplete Shinarump Member ranges from 2.5 to 5.2 m in thickness.

The contact between the Shinarump submember and the Mottled Strata submember is visible in the Little Bown Bench area where the Shinarump submember fills a channel cut into the underlying Mottled Strata submember. This channel is steep-walled, about 1.5 m deep, and widens from approximately 1 m at the base to 1.5 m at the top (Fig. 12). Immediately above the steep-walled channel lies a broader, 40-m-wide channel also filled with the Shinarump submember.

Beds of poorly sorted conglomerate and coarse-grained, cross-bedded sandstone of the upper part of the Shinarump submember fill channels cut into medium-grained sandstone near the base of the submember in both the Little Bown Bench and Circle Cliffs areas (Appendix). The conglomerate is composed of clasts of red and black chert, white and gray shale, and quartz. Clasts have a median diameter of 1 cm with a maximum diameter of 3 cm. The shale clasts are angular and the quartz and chert clasts are rounded.

Figure 12. Channel cut into the Mottled Strata submember and filled with the Shinarump submember of the Shinarump Member in the Little Bown Bench area. Channel is below and to the left of the man with the Jacob's Staff.

The conglomerate is clast supported and has no visible internal structure. It occurs in 3- to 10-cm-thick, laterally discontinuous lenses.

Where conglomerate lenses are absent, the sandstone contains rip-up clasts of finer-grained sandstone (Appendix). These clasts, some preserving relict bedding, are variable in size with some clasts as large as 12 cm by 5 cm. The size and roundness of sandstone clasts increase up section.

The sandstone in the Shinarump submember is well sorted, medium grained, silica cemented and is composed of subangular clasts that are 80 to 90% quartz. In the Little Bown Bench area, some larger rip-up clasts of well sorted, fine-grained sandstone occur in the medium-grained sandstone, but they make up less than 1% of the unit (Appendix).

The Shinarump Member contains mainly angular, wedge-planar cross-beds interbedded with sinusoidal- and parabolic-trough cross-beds and ripple laminae in the Badger Butte (Fig. 13) and Wolverine Bench areas, and angular, wedge-planar cross-beds in the Little Bown Bench area (Appendix). The Circle Cliffs area contains sinusoidal-trough cross-beds with horizontal laminae between sets. Cross-bed sets typically are 10 to 15 cm thick; locally, they are up to 60 cm thick. In addition, there are lateral accretion surfaces in the medium-grained sandstone that dip approximately 20° (Fig. 14) and are separated by an average of 5 m of sandstone.

Higher in the Shinarump Member, in the Badger Butte, Little Bown Bench, and Wolverine Bench areas, thin, light-green siltstone layers are interbedded with the medium-grained sandstone (Fig. 15). The layers typically have thicknesses of 10 to 15 cm with maximum thicknesses of 60 cm (Appendix). In the Little Bown Bench area, the

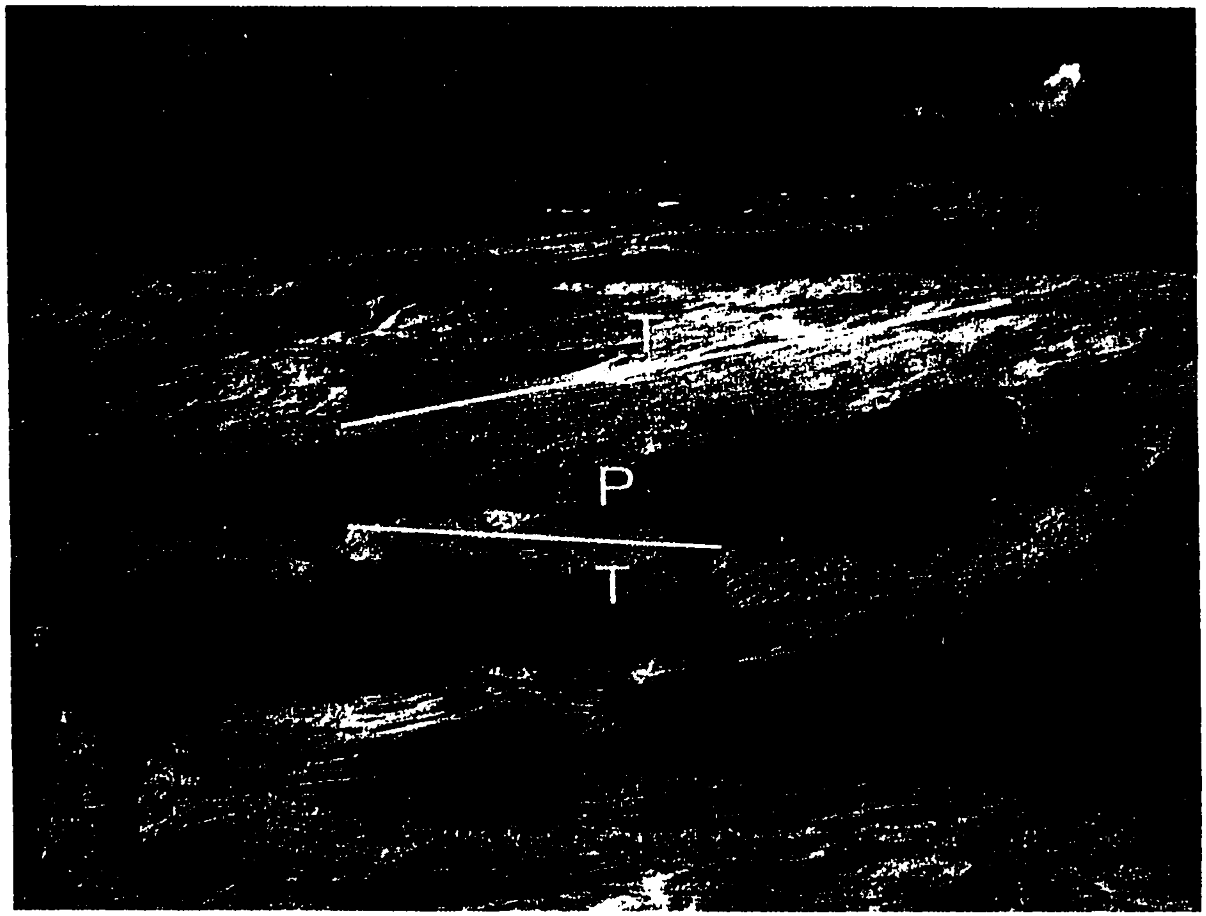


Figure 13. Interbedded trough (T) and planar (P) cross-beds in the Shinarump Member, Badger Butte area (rock hammer is about 33 cm long).

Figure 14. Lateral accretion surfaces in the Shinarump Member, Little Bown Bench area. They dip to the left at the base of this exposure and to the right at the top of this exposure. The rock hammer at the base of this exposure is about 33 cm long.

Figure 15. Thin, silty layers (green in color) interbedded with sandstone at the top of the Shinarump Member in the Badger Butte area. The rock hammer is about 33 cm long.

medium-grained sandstone beds reach a thickness of 1 m and contain rip-up clasts of the siltstone 2 to 3 cm in diameter.

Near the top of the Shinarump Member, thin siltstone layers with ripple laminations increase in frequency (Fig. 16). Cross-bedded sandstone continues to be present, filling 2.5-cm-deep channels cut into the ripple-laminated siltstone (Fig. 17).

Fossils in the Shinarump include fragments of carbonized wood that occur in gravel lenses (Fig. 18) in the Badger Butte and Little Bown Bench areas (Appendix). The wood fragments are surrounded by aureoles of yellow siltstone and appear to be oriented subparallel to one another.

Monitor Butte Member

The Monitor Butte Member was named by Kiersch (1956) for exposures on Monitor Butte just south of the San Juan River in eastern Utah. This member typically consists of greenish-gray bentonitic mudstone with rare beds of fine-grained, clayey sandstone and low-grade coal (Lucas et al., 1997b).

In the study area, two informal submembers of the Monitor Butte Member are present. The lower informal submember consists of interbedded siltstone and sandstone with lenses of poorly sorted gravel. The upper informal submember contains two facies (1) pale-green siltstone with minor amounts of interbedded sandstone and (2) clayey mudstone. Rocks of the interbedded sandstone and siltstone informal submember weather to hematite-stained, resistant ledges. The siltstone facies of the upper informal submember weathers to grayish-green slopes. Both the interbedded sandstone and

Figure 16. Ripple laminations and ripple marks (shown by arrow) in the upper part of the Shinarump Member in the Badger Butte area. Rock hammer is about 33 cm long.

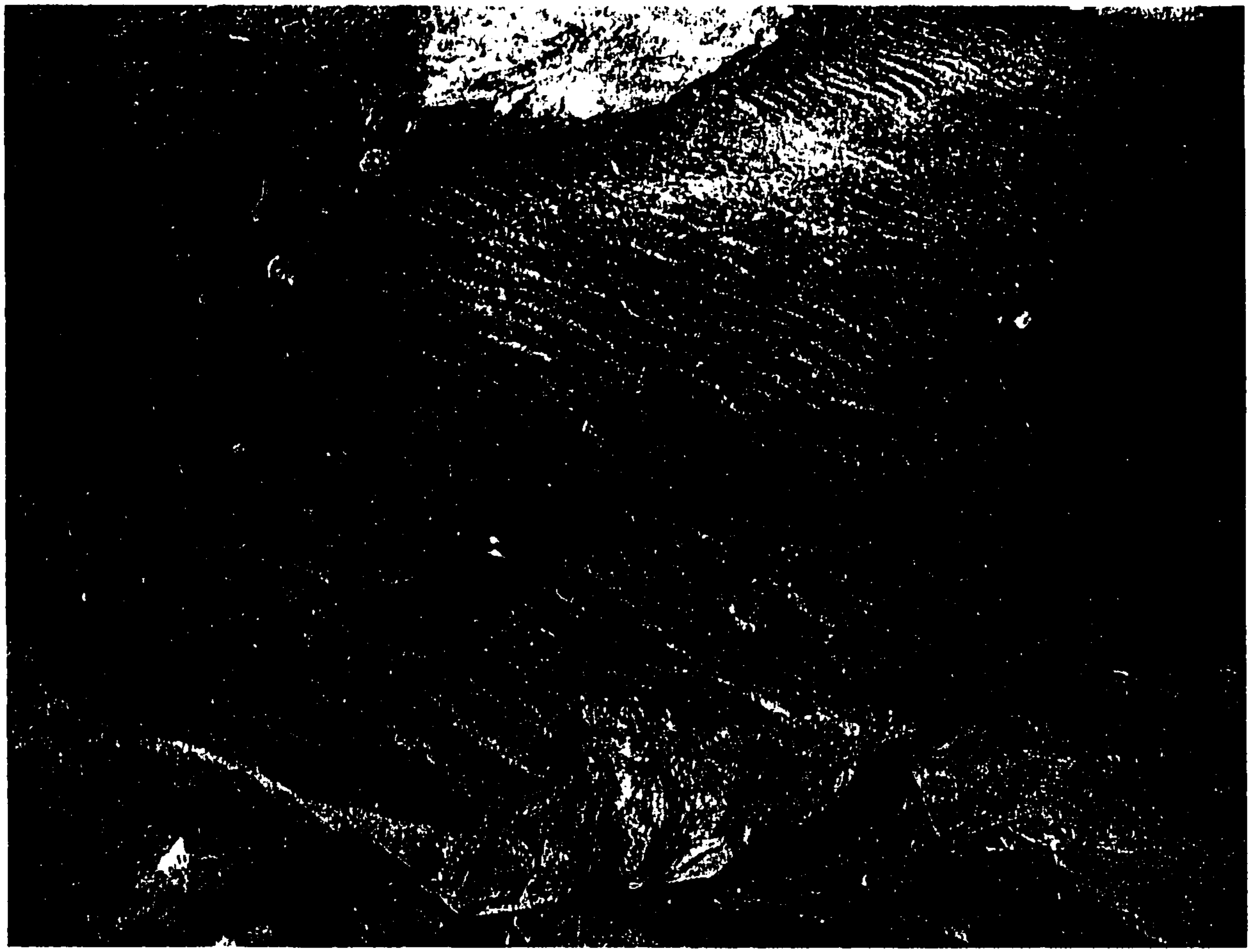


Figure 17. Ripple marks at the top of the Shinarump Member showing a paleoflow of S40°W, Badger Butte area .

Figure 18. Carbonized wood (shown by arrow) in the Shinarump Member near the contact with the Monitor Butte Member in the Little Bown Bench area (yellow staff on far right is 1 m long).

siltstone informal submember and the siltstone facies are grayish green on fresh surfaces with the sandstone having small red mottles. The mudstone facies of the upper informal submember is red, purple, or green on both fresh and weathered surfaces.

The Monitor Butte Member conformably overlies the Shinarump Member. The contact between the two members is placed at the lowest occurrence of symmetrical ripple marks (Fig. 16) as suggested by Stewart (1972a). The Monitor Butte Member ranges in thickness from 8.0 to 14.0 m.

The lower informal submember of the Monitor Butte Member, the interbedded sandstone and siltstone informal submember, displays many of the same features as the uppermost parts of the Shinarump Member. The sandstone is well sorted, medium grained, silica-cemented, and composed primarily of subangular quartz clasts. The sandstone is bedded mainly in angular, wedge-planar cross-beds. Rare lenses of poorly sorted conglomerate are similar to the conglomerate lenses in the Shinarump Member. This unit ranges from 1.3 to 15 m thick across the area of study.

The two facies of the upper informal submember appear to grade laterally into one another (Appendix). The first facies, the pale-green, micaceous siltstone facies (Fig. 19), contains lenses of resistant sandstone. This facies is poorly lithified and slope-forming. Although the contact between the pale-green siltstone facies and the underlying sandstone and siltstone facies is not exposed, it probably is conformable. This facies ranges from 0 to 1.6 m thick across the area of study.

The pale-green siltstone facies has a distinctive gray-green color and is laminated in millimeter-scale layers with symmetrical ripple marks that increase in abundance

Figure 19. Distinctive green color and appearance of the siltstone facies of the Monitor Butte Member in the Badger Butte area (this exposure is up to 4 m thick in center).

upward. The resistant sandstone is typically very fine grained, well sorted, homogeneous, micaceous, quartz-rich, well cemented, and ripple laminated, and has platy parting. Black minerals accentuate some laminations and parting in the sandstone. Near the top of the exposure of the Monitor Butte Member, laminae thin to 1 mm and ripple marks become more abundant. Laminae generally are laterally discontinuous, and the resistant cross-bedded sandstone fills 10-cm-deep channels cut into the ripple-marked siltstone.

The clayey mudstone facies contains red, purple, and green mudstone. The mudstone is divided into angular to subangular, platy blocks and contains calcite nodules, and mottles. These layers occur in the Wolverine Bench area. This facies ranges from 0 to 5.0 m thick across the area of study.

Fossils occur in the lower interbedded sandstone and siltstone submember and in the pale-green siltstone facies of the upper submember. In the interbedded sandstone and siltstone submember, carbonized wood fragments are present in non-imbricated, poorly sorted gravel lenses. The wood fragments are up to 20 cm wide and 1 m long and commonly occur at the top of lateral accretionary sets, as is the case in the Little Bown Bench area.

In the pale-green siltstone facies in the Badger Butte area, carbonized leaves occur in lenses of the resistant sandstone (Appendix). The leaves occur on bedding surfaces, including some surfaces with symmetrical ripple marks. Bedding is not always apparent, and the leaves commonly occur on parting planes in otherwise apparently unbedded sandstone.

Bluewater Creek Member

The Bluewater Creek Member was named by Lucas and Hayden (1989) for exposures in the Fort Wingate quadrangle of west-central New Mexico. It is dominated by red mudstone with interbeds of laterally persistent, bench-forming, ripple-laminated litharenite (Lucas et al., 1997a).

In the study area, the Bluewater Creek Member contains three facies, (1) a limestone-pebble conglomerate, (2) a clayey mudstone, and (3) a discontinuous, bench-forming, ripple-laminated sandstone. The Bluewater Creek Member unconformably overlies the Monitor Butte Member and ranges in thickness from 0 to 7.4 m.

The first facies, a limestone-pebble conglomerate, here called the Wolverine conglomerate, occurs in a north-striking band along the eastern flank of Wolverine Bench (Fig. 20). The Wolverine conglomerate is up to 4.2 m thick and fills a channel cut into the underlying Monitor Butte Member (Fig. 21). It is brown on weathered surfaces and white to light gray on fresh surfaces. This conglomerate contains poorly sorted clasts composed predominantly of limestone of two types: internally bedded clasts and internally unbedded clasts (Appendix). The clasts are angular to subangular, imbricated, oblate spheroids, which average 5 cm in length by 1 to 2 cm in width, although some are as large as 20 cm^2. The bedded clasts appear lacustrine in origin. The unbedded clasts have internal structures similar to those in carbonate nodules, which weather out of mudstones throughout the study area. The Wolverine conglomerate is clast supported with a matrix of medium- to coarse-grained sandstone. This facies ranges from 0 to 4.2 m thick across the area of study.

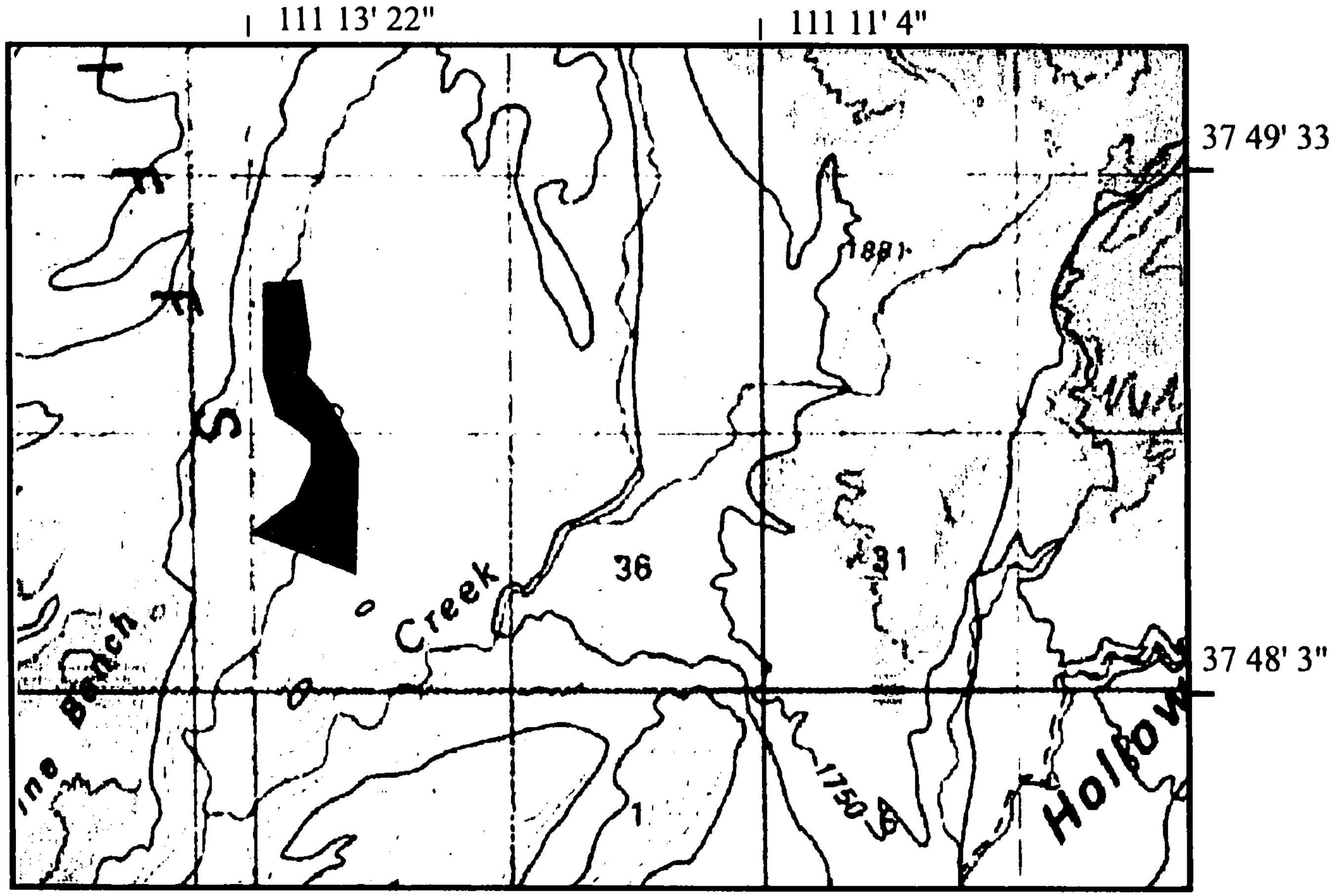


Figure 20. Location of the Wolverine conglomerate in the study area (shown by blue shaded area).

Figure 21. Wolverine Conglomerate filling a channel cut into underlying Monitor Butte Member. This outcrop is along the southeast flank of Wolverine Bench, just north of the fence that forms the northern boundary of the Wolverine Petrified Wood Area. The woman in the photo is about 1.6 m tall.

The second facies, a clayey mudstone, weathers to light red, light green, or light purple slopes and is dark brown or red with green mottles on fresh surfaces. The mudstone facies contains oblong, white, 0.5- to 1.5-cm-diameter calcite nodules. The mudstone is either structureless or breaks into angular-blocky structures 1 mm across. In the mudstone facies in the Little Bown Bench area, the mudstone is structureless and sandy, but still contains calcite nodules (Appendix). Interbedded with the mudstone are sandstone laminae. The mudstone facies appears to conformably overlie the Wolverine conglomerate and to interfinger with the third facies of the Bluewater Creek Member, but the contact between these facies is generally not exposed in the study area. The mudstone facies ranges from 0 to 5.0 m thick across the area of study.

The third facies of the Bluewater Creek Member, the sandstone facies, is purple, red, and/or brown in color on weathered surfaces with alternating beds of white and light purple or light red on fresh surfaces. It is resistant to weathering and forms a distinctive ledge. The sandstone facies is best exposed in the Badger Butte area where it fills a channel cut through the mudstone facies and into the Monitor Butte Member (Fig. 22). Where the channel is deepest, the sandstone has current ripple laminations (Appendix). At the channel margins, symmetrical ripple marks and horizontal laminae become dominant. Laminae are 1 mm thick and occur in 0.1- to 1.0-m-thick sets. Sandstone in this member is fine grained and is composed of well sorted, angular to sub-angular grains of quartz, feldspar, and green minerals. A small amount of calcite cement is present. The contact between the sandstone facies and the underlying mudstone facies may either be gradational or erosional. This facies ranges from 0 to 5.0 m thick across the area of study.

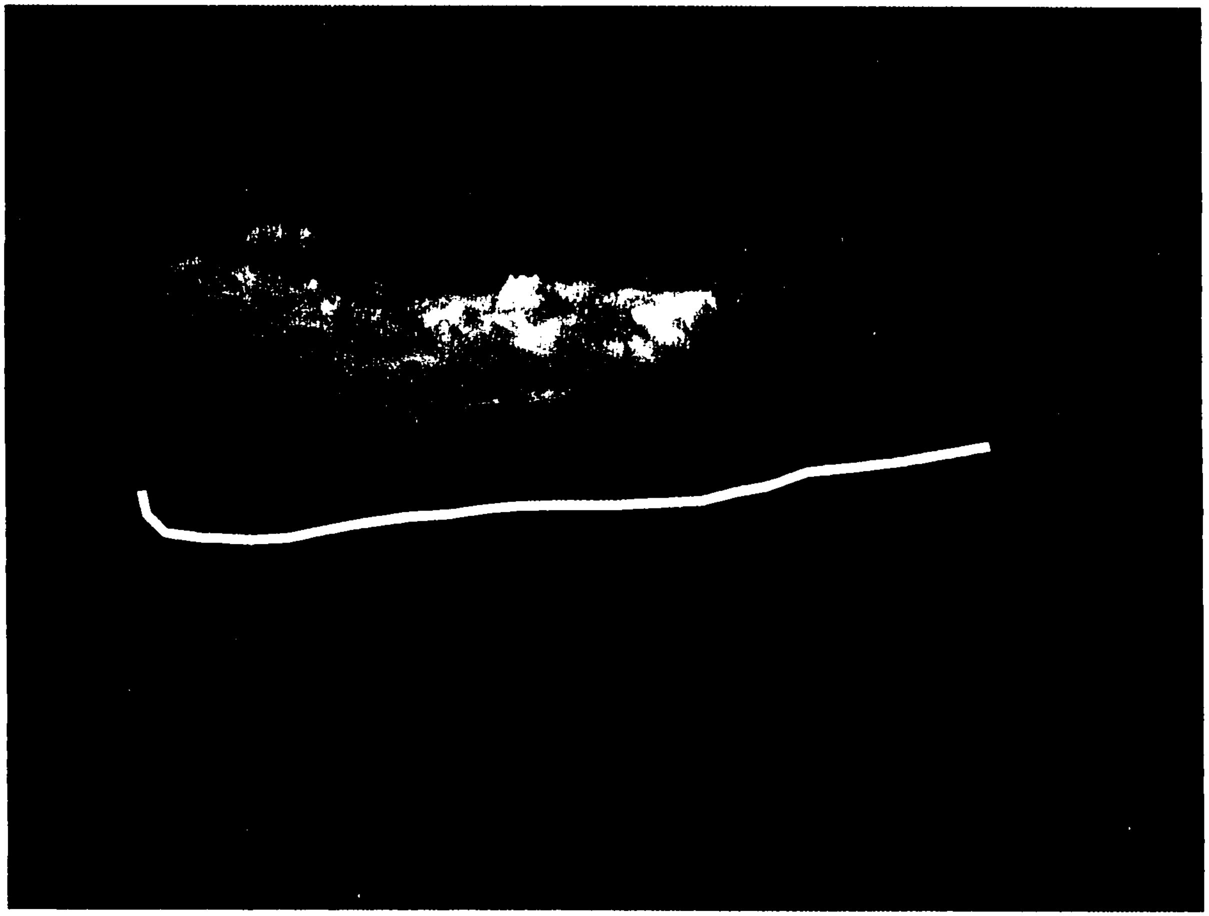


Figure 22. Sandstone facies of the Bluewater Creek Member filling a channel cut into the Monitor Butte Member in the Badger Butte area.

Fossils occur only in the sandstone facies of the Bluewater Creek Member. Carbonized leaves and vertical burrows occur on bedding surfaces at the channel margins.

Petrified Forest Member

The Petrified Forest Member was named by Gregory (1950) for exposures in Zion National Park, Utah. In the study area, the Petrified Forest Member contains three submembers, (1) the Lower Petrified Forest submember, (2) the Moss Back submember, and (3) the Upper Petrified Forest submember. The Petrified Forest Member conformably overlies the Bluewater Creek Member, and the contact between the two members is defined by the lowest occurrence of laterally extensive bentonitic mudstone above the sandstone facies, the highest sandstone lens of the mudstone facies, or the Wolverine conglomerate. The Petrified Forest Member ranges from 60.5 m to 83.9 m in thickness.

Lower Petrified Forest Submember. All across the Colorado Plateau, the Lower Petrified Forest consists of bentonitic mudstone with locally extensive interbeds of biotite-rich litharenite. Local informal units within the Lower Petrified Forest submember in the Petrified Forest National Park include the Newspaper Sandstone, Rainbow Sandstone, and Brown Sandstone (Lucas, 1993, 1994).

In the study area, the Lower Petrified Forest submember is dominated by clayey mudstone with lenses of sandstone. The mudstone is inferred to be bentonitic based on its distinctive popcorn weathering on slope surfaces (Grim and Guven, 1978; Gray et al., 1989), its waxy luster, and its expansion when wet (Allen, 1930). This submember is commonly red, purple, yellow, brown, or green on both weathered and fresh surfaces; colors may be uniform or mottled with splotches of a contrasting color (Fig. 23). The Lower Petrified Forest submember ranges from 13.0 m to 30.7 m in thickness.

In the Lower Petrified Forest submember, mottled mudstone is common throughout the study area with mottles typically having irregular shapes and rounded edges. The material in the mottles is the same as that in the remainder of the mudstone. Mottles typically are scattered randomly throughout the mudstone, but exceptions do occur. In Lizard Butte, near the middle of the submember, mottles increase in abundance upward (Appendix).

On fresh surfaces, the mudstone typically breaks into angular to subangular, blocky structures; granular or platy structures also occur, but are more rare. Rarer still are outcrops in which the mudstone is massive. The angular and subangular blocks have average sizes up to 1 cm across, and the surfaces of the blocks are smooth with slickensides. Granular structures are less than 1 cm in width, typically only 1 to 2 mm, with obscure slickensides. Granular structures occur in unit 1 in both the Wolverine Bench and the Lizard Butte areas (Appendix). Platy structures have average lengths up to 1 cm and slickensides on their flat surfaces. Platy structures occur in unit 1 in the Badger Butte area (Appendix), where they grade vertically into angular blocky structures.

The mudstone outcrops contain abundant, 1- to 5-cm-diameter, calcite nodules. Nodules may be arranged in layers or they may be scattered throughout mudstone outcrops (Appendix). Where nodules are scattered, their abundance can increase or decrease vertically. For example, in the Wolverine Bench area, nodules decrease in

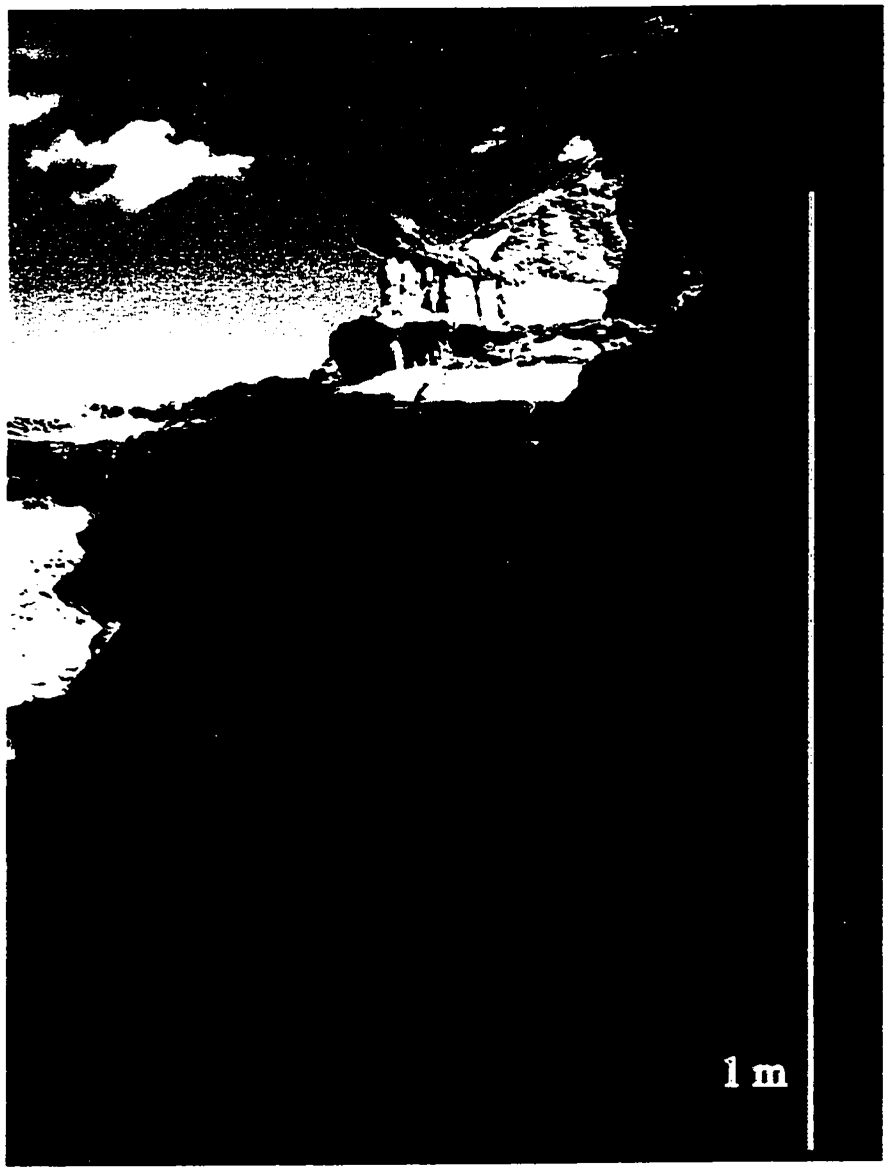


Figure 23. Mottled mudstone in the Lower Petrified Forest submember in the Badger Butte area.

abundance upward, but in both the Badger Butte and Circle Cliffs areas, nodules increase in abundance upward.

The surfaces of nodules are smooth or botryoidal with shapes ranging from spherical to oblate (Fig. 24). Internally, the nodules are made up of intergrown calcite crystals and carbonate-cemented mud. The structures formed by these components differ from nodule to nodule, but they commonly assume a star- or flower-like pattern. The exception to this pattern occurs near the surface of some nodules, where concentric rings occur.

Calcite layers occur in the Badger Butte area. These 5-mm-thick layers are composed of very thin, vertically oriented crystals, similar to those in the Monitor Butte Member.

In unit 1 of the Lower Petrified Forest submember in the Wolverine Bench area, a discontinuous, wavy-bedded, fine-grained, carbonaceous sandstone composed of 0.1- to 0.5-mm-thick laminae crops out (Appendix).

The mudstone of the Lower Petrified Forest submember weathers to slopes that generally are covered by expanded clay crusts. Where calcite nodules are present in the mudstone, the slopes are covered by fragmented nodules.

Trace fossils in the Lower Petrified Forest submember consist of elongate areas of a mudstone of a contrasting color that probably outline root or burrow traces. These features are apparent in the Wolverine Bench, Circle Cliffs, and Lizard Butte areas (Appendix).

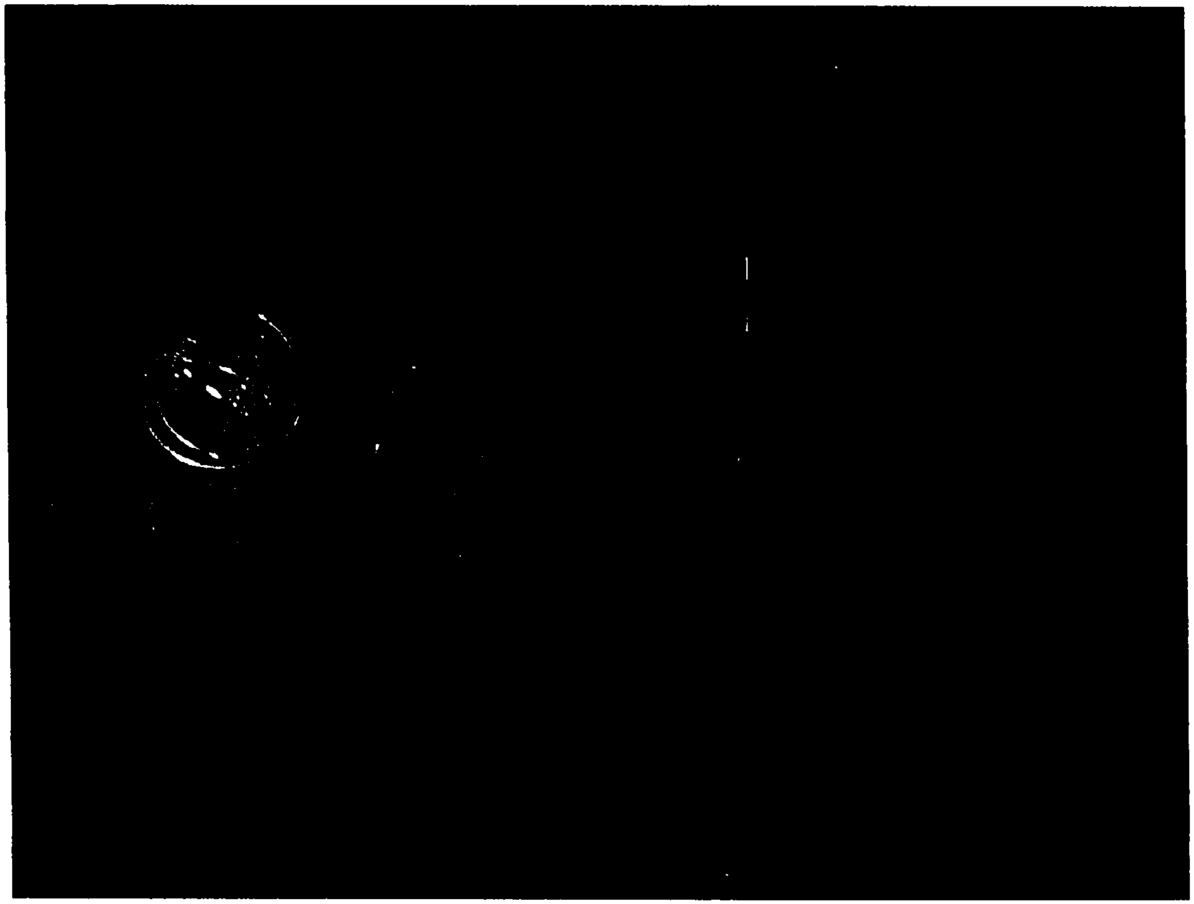


Figure 24. Internal (left) and external (right) appearance of carbonate nodules from the Petrified Forest Member.

Moss Back Submember. The Moss Back submember was named by Kiersch (1955) for Moss Back Butte, Utah, which is just west of Natural Bridges National Monument (Fig. 2). Across the Colorado Plateau, the Moss Back submember is predominantly trough-cross-bedded litharenite and chert-pebble conglomerate. It is laterally equivalent to the Sonsela Sandstone (Lucas et al., 1997a, b), but can be differentiated from the Sonsela Sandstone by its larger percentage of intraformational clasts, including mudstone and reworked calcite nodules (Heckert and Lucas, 1996).

According to Lucas (1993, 1994), the Moss Back submember has an erosional contact with the underlying Lower Petrified Forest submember, and it fills channels up to 20 m deep. This erosional surface is present across the Colorado Plateau and is the TR-4 unconformity which approximates the Carnian-Norian boundary (Lucas, 1993, 1994; Heckert, 1995; Heckert and Lucas, 1996; Lucas et al., 1997a, b).

In the study area, the Moss Back submember generally contains a basal conglomerate that grades upward into fine-grained brown sandstone, then to lavender sandstone, then to white sandstone, and then finally to red sandstone. The lower sequence of conglomerate, lavender sandstone, and white sandstone is not complete in all locations, and in some areas, units are juxtaposed differently. The red sandstone, however, is present at the top of the sequence at all locations. Colors on weathered surfaces are very similar to colors on fresh surfaces. All of the sandstone in the Moss Back submember weathers into distinctive "toadstool" shapes (Fig. 25).

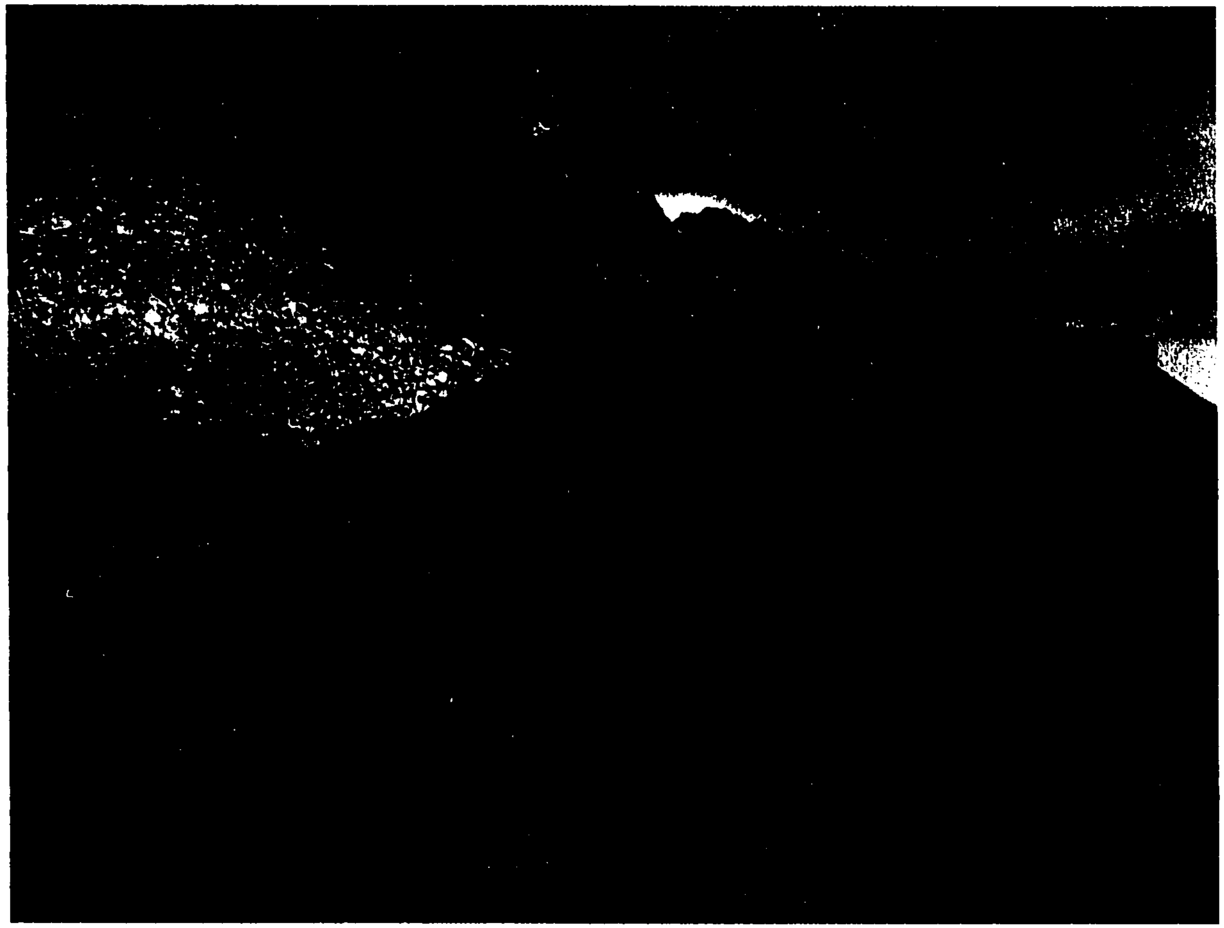


Figure 25. Moss Back submember weathering to distinctive toadstool shapes in the Wolverine Bench area. Rock hammer is about 33 cm long.

In all areas, the basal conglomerate or sandstone of the Moss Back submember unconformably overlies the mudstone of the Lower Petrified Forest submember. The Moss Back submember ranges from 5.6 to 7.2 m in thickness.

In the Lizard Butte, Circle Cliffs, Badger Butte, and Wolverine Bench areas, the lower part of the Moss Back submember consists of fine-grained, well indurated, pebbly sandstone and conglomerate. The pebbles are predominantly reworked limestone nodules and sandstone and red mudstone rip-up clasts (Appendix). In the Wolverine Bench area, the sandstone is calcite cemented and is cross-bedded in 10-cm- to 1.0-m-thick sets. Symmetrical ripple marks are apparent on bedding surfaces. In the Badger Butte area, the basal conglomerate is calcite cemented and clast supported with angular or platy, mudstone rip-up clasts up to 1 cm in diameter that fine upward. The surface of the conglomerate appears porous indicating that some clasts have been preferentially weathered out. The matrix is fine grained, well sorted sandstone composed of quartz, feldspar, and limited amounts of green and black minerals.

In the Circle Cliffs area, the basal conglomerate of the Moss Back submember is matrix supported, calcite cemented, and slightly porous on weathered surfaces. Clasts are angular to subangular oblate spheroids of light brown siltstone, black shale, brown limestone, conglomerate, and red mudstone (Appendix), and have average sizes of 5 x 2 cm but are up to 20 cm in diameter. There is no apparent structure to the conglomerate. The matrix is coarse-grained, poorly sorted sandstone. Where the conglomerate is absent, a fine-grained, brown sandstone containing angular, wedge-planar cross-laminae on a scale of 6 mm are present at the base of the submember.

In the Lizard Butte area, the basal unit of the Moss Back submember consists of well indurated, pebbly sandstone containing pebbles of red mudstone and large sandstone rip-up clasts.

Above the basal conglomerate is a resistant, slightly calcareous, very hard sandstone. The sandstone is fine grained, well sorted and composed of quartz, feldspar, and limited amounts of a green mineral. Cross-bed sets are up to 23 cm thick with some lenses of smaller sets (2 cm thick) and rare rib and furrow structures. This sandstone fills a channel cut into the underlying unit.

The next higher beds of the Moss Back submember are composed of lavender and/or white, medium-grained, well sorted, parabolic trough-cross-bedded sandstone (Appendix). In the Lizard Butte area the lavender sandstone has very low-angle trough cross-beds; in the Circle Cliffs area, the white sandstone contains angular, wedge-planar cross-beds. In the Badger Butte area, the white sandstone has very low-angle trough cross-beds, and in the Wolverine Bench area, the lavender sandstone contains very low-angle trough cross-beds and lateral accretion surfaces. In most areas, the lavender sandstone conformably overlies the underlying sandstone, although in the Little Bown Bench area the contact is erosional.

In the Badger Butte, Little Bown Bench, and Circle Cliffs areas, the lavender and/or white sandstone has been cut by a channel filled with a clast-supported conglomerate that is as much as 20 cm thick (Fig. 26). The conglomerate contains predominantly angular rip-up clasts of mudstone with limited amounts of limestone up to 5 cm in diameter (Appendix). The matrix is calcite-cemented sandstone of the same

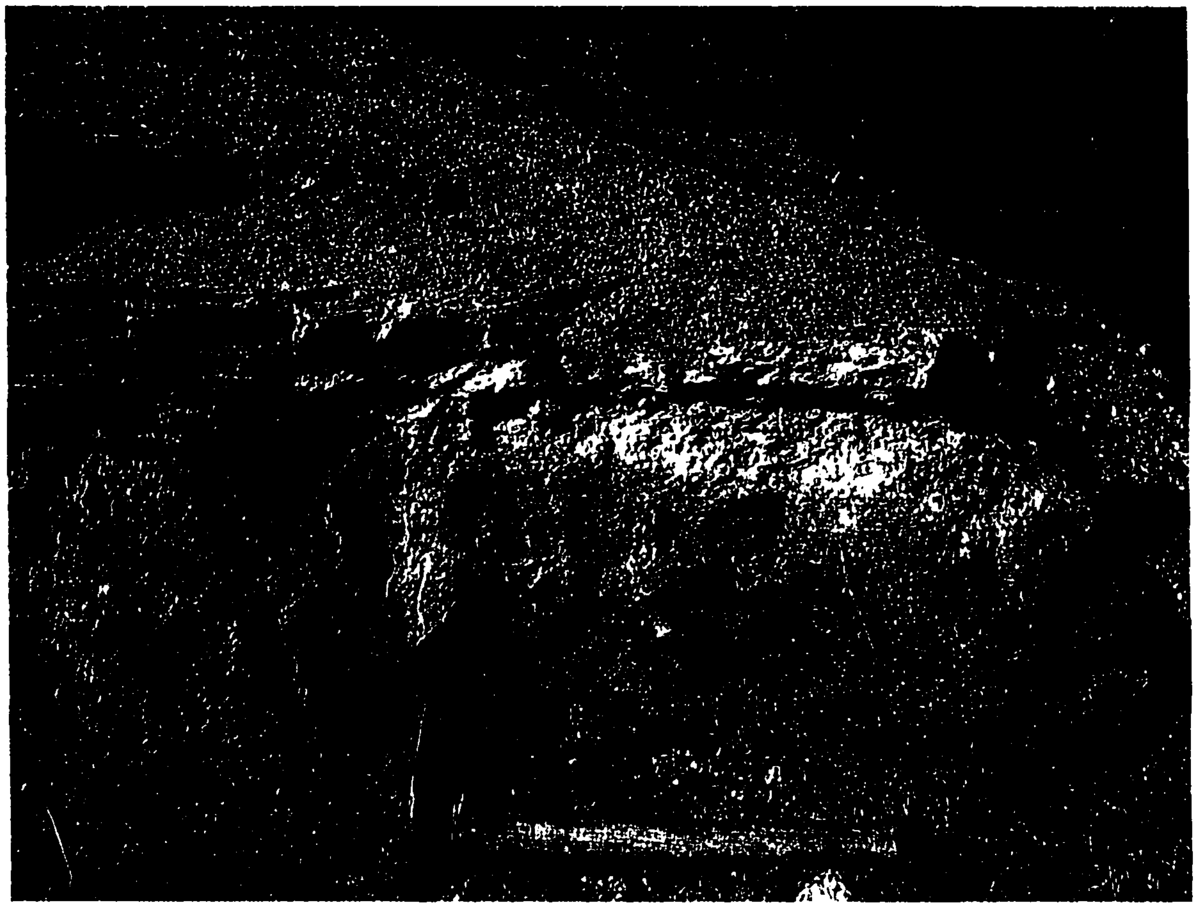


Figure 26. Conglomerate-filled scour cut into the lavender sandstone of the Moss Back submember in the Lizard Butte area; rock pick is approximately 40 cm long.

composition as the underlying sandstone with an increasing amount of a magnetite vertically. The conglomerate is angular, wedge-planar cross-bedded in the Circle Cliffs area, where 0.25-m-thick sandstone lenses are also present.

Above the conglomerate is a lavender and/or white sandstone unit, similar to the lavender and/or white sandstone below the conglomerate. The transition between these units is gradational.

Above the lavender/white sandstone is a medium-grained, well sorted, red sandstone unit. In the Little Bown Bench and Circle Cliffs areas, this sandstone contains angular, wedge-planar cross-beds. In the Lizard Butte and Wolverine Bench areas, there are trough cross-beds. Laminations and beds are 2 mm to 2 cm thick, with 2-cm-thick layers distinguished by the presence of magnetite (Appendix). These layers are cemented together in sets with an average thickness of 7 cm.

Interbedded with the sandstones of the Moss Back submember are clayey mudstone lenses with an average thickness of 5 cm (Appendix). The mudstone is divided into centimeter-scale platy structures. It is red with green mottles and is carbonate cemented. Yellow siltstone, similar to that associated with carbonized logs in the Shinarump and Monitor Butte members, occurs in the mudstone in the Wolverine Bench area. Because of the similarity to the siltstone in the Shinarump and Monitor Butte members, which is associated with logs, this siltstone may also suggest the presence of organic material in the mudstone.

The Moss Back submember is the richest petrified wood-bearing layer in the study area. The wood is encased in cross-beds of the white and/or lavender sandstone in the lower part of the submember (Fig. 27). In addition to petrified wood, bone fragments occur in the Moss Back submember in the Badger Butte and Lizard Butte areas (Appendix).

Upper Petrified Forest Submember. The Upper Petrified Forest submember consists of the part of the Petrified Forest Member above the Moss Back submember (Lucas et al., 1997b). It is composed primarily of reddish-brown bentonitic mudstone with laterally extensive beds of sandstone and conglomerate (Gregory, 1950; Lucas, 1993, 1994). The Flattops sandstones and Black Forest volcaniclastic bed of the Petrified Forest National Park (Lucas, 1993, 1994) and the Capitol Reef bed of the Capitol Reef area (Stewart et al., 1972a) are names of local sandstones within the Upper Petrified Forest submember.

In the study area, the Upper Petrified Forest submember is defined by the dominance of clayey, bentonitic mudstone in hues of red, purple, and green, essentially identical to those in the Lower Petrified Forest submember. There is also sand, occurring sporadically as scattered grains and lenses within the mudstone and as one widespread layer informally called the Zebra sandstone. The contact between the Upper Petrified Forest submember and the underlying Moss Back submember is conformable, and is placed at the lowest appearance of continuous mudstone beds. The Upper Petrified Forest submember ranges from 30.7 to 47.9 m in thickness.

Mottles are common throughout the Upper Petrified Forest submember and are generally green or red and irregularly shaped with rounded edges. The material in the

Figure 27. Permineralized wood in the white and lavender sandstone interval, Moss Back submember, Lizard Butte area. Rock hammer on the log is about 33 cm long.

mottles generally is similar to that in the remainder of the mudstone. One exception occurs in unit 15 in the Wolverine Bench area (Appendix) where green motties in a lavender mudstone appear to be better lithified than the surrounding mudstone. In addition, these mottles break into smaller angular blocky structures than the parent mudstone and were observed to hold moisture longer than the surrounding mudstone.

Mottles typically are scattered randomly throughout the mudstone, although exceptions do occur. In the Wolverine Bench area, the upper part of the unit has a layer of concentrated green mottles (Appendix). In the Badger Butte area mottles increase in abundance vertically four times in the lower part and once again in the upper part of the submember (Appendix). This also happens twice in the upper part of the submember in the Circle Cliffs area (Appendix).

The mudstones may be divided into blocky, platy, or granular structures or they may be massive. Blocky structures are the most common and occur throughout the submember. Platy structures occur in the middle of the submember in the Wolverine Bench area where they grade downward into angular blocky structures (Appendix). Platy structures occur in the lower part of the submember in the Circle Cliffs area where they grade upward into granular structures (Appendix). Massive mudstones occur in the upper part of the submember in the Wolverine Bench area, the Lizard Butte area, and the Little Bown Bench area (Appendix).

Abundant calcite nodules with diameters of 1 to 50 cm occur throughout this submember. Nodules increase vertically, occur in layers, or are scattered throughout the mudstone. The mudstones are generally poorly exposed and weather to slopes commonly covered by fragmented calcite nodules. The nodules are essentially identical to those in the Lower Petrified Forest submember.

Discontinuous sandstone beds are scattered throughout the Upper Petrified Forest submember. One such bed in the Little Bown Bench area contains well sorted, fine- to medium-grained, homogeneous sandstone with parabolic-tabular cross-beds (Appendix). The sandstone beds overlie erosional surfaces.

Above these thin, localized, sandstone beds a sandstone interval, called the Zebra sandstone in this study, is present in all stratigraphic sections (Appendix). This sandstone is moderately sorted, fine to medium grained, and composed of angular to subangular grains with rare gravel clasts and interbedded conglomerate layers.

Throughout the study area, the Zebra sandstone has alternating green, lavender, brown and yellow beds on both weathered and fresh surfaces (Fig. 28), although weathered surfaces may also be hematite stained. It is composed of alternating resistant and non-resistant beds.

The contact between the Zebra sandstone and the underlying unit is erosional. The base of the Zebra sandstone generally is composed of cross-bedded, medium-grained sandstone that fills channels cut into the underlying mudstone. Sand grains are up to 0.8 mm in diameter; the median diameter is 0.4 mm. A basal conglomerate is present only in the Circle Cliffs area where it is resistant, composed of moderately to poorly sorted, angular, mudstone rip-up clasts and some limestone clasts. Clasts in the conglomerate are up to 20 cm in diameter, with an average size of 5 x 2 cm. The Zebra sandstone ranges from 8.1 to 18.3 m in thickness.

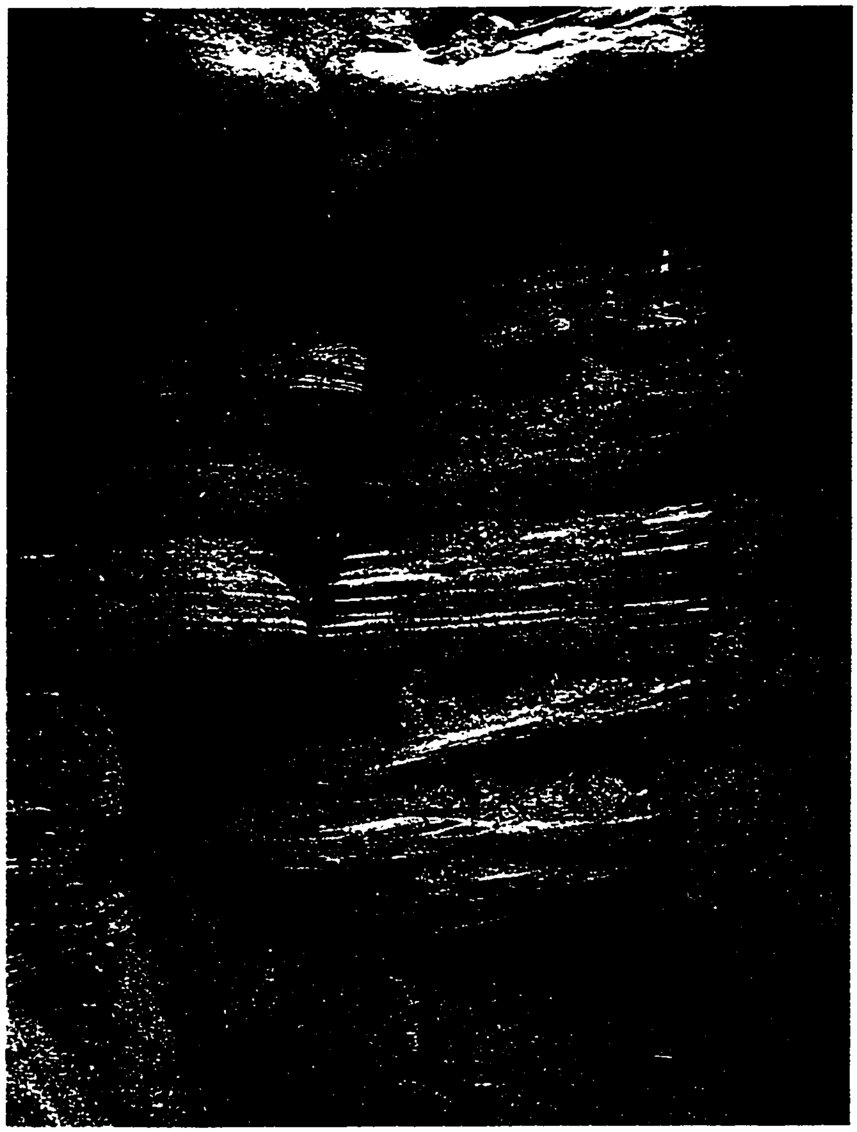


Figure 28. The Zebra Sandstone in the Wolverine Bench area (rock pick is about 33 cm long).

Beds typically have sinusoidal-tabular and angular, wedge-planar cross-beds, although in the Circle Cliffs area there are wedge-planar cross-beds, and in the Lizard Butte area there are parabolic-tabular cross-beds. Thin sets (10 cm thick) typically are interbedded with thicker sets (50 cm thick). In the Badger Butte area, there are rip-up clasts of red clay in the upward-fining sandstone, and the sandstone breaks into platy structures with widths up to 1 cm.

In the Badger Butte, Circle Cliffs, Lizard Butte, and Little Bown Bench areas, the sandstone is interbedded with clast-supported conglomerate made up of rip-up clasts of mudstone and sandstone with limited amounts of limestone. Clasts are angular and less than 1 cm in diameter.

In the Circle Cliffs, Lizard Butte, and Little Bown Bench areas, the Zebra sandstone contains petrified wood similar in size to the wood in lower units, but in much smaller amounts. Because it is so scarce, measurements could only be made in the Lizard Butte area where 0.25-m-diameter petrified logs are oriented N60°E (Appendix).

Above the Zebra sandstone is mudstone with rare, isolated sandstone or conglomerate layers lying on erosional surfaces (Appendix). For example, in the Lizard Butte area there is a tabular-planar cross-bedded sandstone bed above the Zebra sandstone (Appendix).

Owl Rock Member

The Owl Rock Member was named by Witkind and Thaden (1963) for exposures near Owl Rock in the Monument Valley area, Arizona. Regionally, this member is composed of pale-red litharenite and orange-pink silty mudstone with limited amounts of limestone (Lucas, 1993, 1994). Because of its distinctive appearance and great lateral continuity, it is a useful marker bed (Robertson, 1981). The Owl Rock Member conformably overlies the Petrified Forest Member (Harris et al., 1997).

In the field area, the Owl Rock Member is composed of well lithified, commonly dolomitic, mudstones that have a layered or blocky appearance (Fig. 29). The Owl Rock Member is slightly calcareous, and it is white to light green on fresh surfaces with the amount of green increasing upward and hematite stained or red and green mottled on weathered surfaces. The base of this member is defined by the dominance of irregularly-shaped, siliceous nodules, and the presence of resistant, dolomitic mudstones (Appendix). The contact between the Owl Rock and the underlying Petrified Forest Member is commonly obscured, but appears conformable. The slopes covering the contact are up to 8.9 m thick (Appendix) so the thicknesses measured may not always be accurate. Regardless, the thickness of the Owl Rock Member is highly variable; exposures of this member range in thickness from 14.7 to 43.3 m.

The dolomitic mudstone layers of the Owl Rock Member are commonly divided into angular to sub-angular blocks with average widths up to 15 cm. These blocky layers are most apparent on 0.3- to 7.7-m-high steps that occur throughout exposures of this member. The steps grade upward into slopes characterized by a decrease in the size of the angular to sub-angular blocks.

The most dolomite-rich layers within the Owl Rock are in the Wolverine Bench area. The dolomite occurs as nodules that increase in abundance vertically until they form

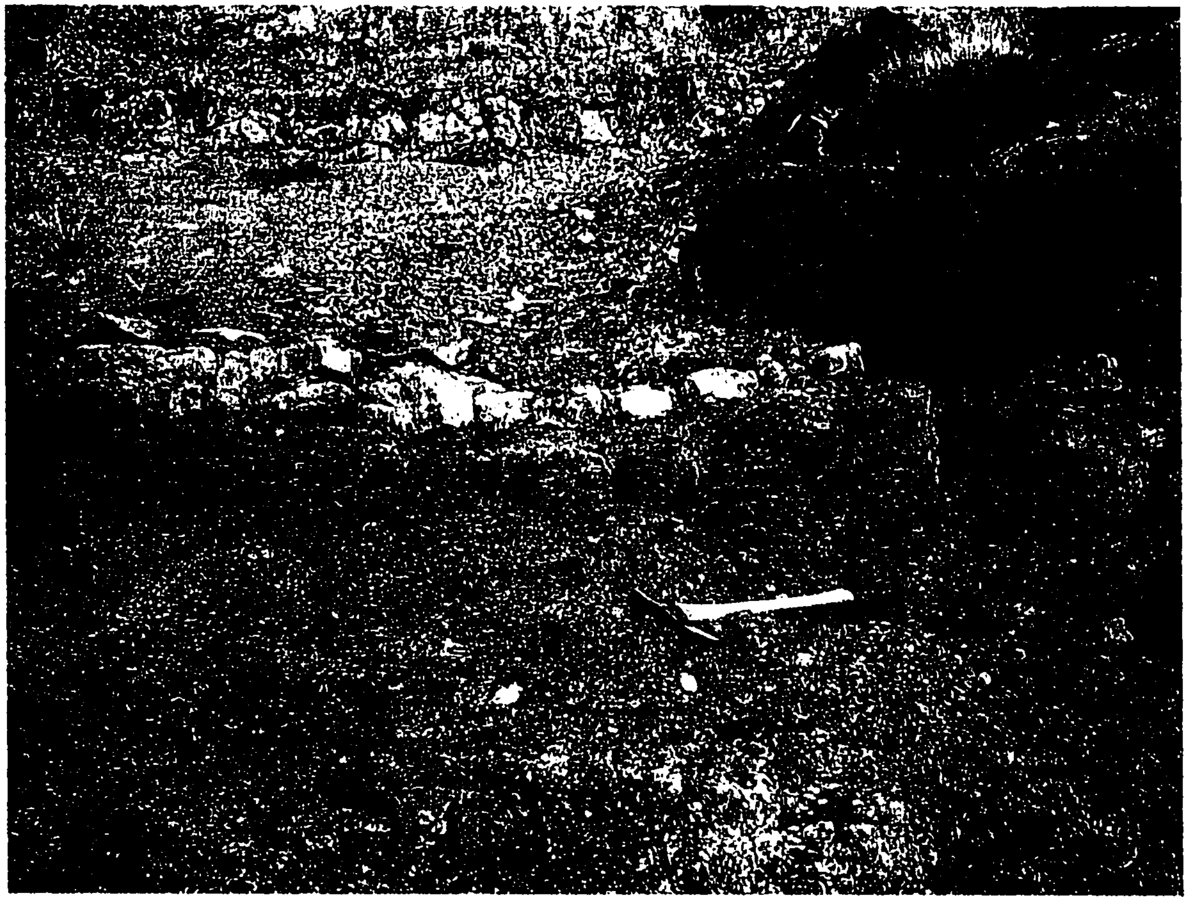


Figure 29. Distinctive stepped morphology of the Owl Rock Member.
The rock hammer in the foreground is about 40 cm long.

cohesive layers with a columnar morphology. There are some oblong clay nodules 2 x 1.5 cm in size and thin, undulating layers of mudstone with thicknesses of 1 cm, some with symmetrical ripple laminations. The mudstone layers throughout the unit are commonly combined into sets up to 8 cm thick.

Halos and cylindrical trace fossils inferred to be root traces or burrows are preserved in the Owl Rock Member in all five measured sections.

Church Rock Member

The Church Rock Member was named by Stewart (1957) for a locality in Monument Valley. This unit is dominated by reddish-brown and red, non-bentonitic siltstone and horizontally or ripple-laminated sandstone (Lucas, 1991; Stewart et al., 1972a, b). There are rare interbeds of limestone, siltstone, quartzite-pebble conglomerate, and trough cross-bedded sandstone (Lucas, 1991). This member is reddish-brown to red on both weathered and fresh surfaces. The Church Rock Member forms an erosional contact with the underlying Owl Rock Member; this erosional surface represents an unconformity that marks the end of the Norian (Lucas et al., 1997a, b).

In the study area, the Church Rock Member contains two facies. Generally, the mudstone facies occurs below the sandstone facies, but in the Little Bown Bench area, the mudstone facies occurs above the sandstone facies. The Church Rock Member ranges in thickness from 2.1 to 5.9 m with the contact between it and the underlying Owl Rock Member placed at the lowest appearance of non-bentonitic, red mudstone or red sandstone. There is no apparent evidence of erosion between the Church Rock Member and the underlying Owl Rock Member

The mudstone facies is dominated by non-bentonitic, clayey mudstone that appears mottled dark red to brownish red and green on weathered surfaces, and mottled light red and green on fresh surfaces. In the lower exposures of the unit in all areas, green mottles are round and regularly shaped. Near the top of the unit, mottles occur in layers with average thicknesses of 5 cm. Clay nodules occurring throughout the member have average sizes of 1 cm by 2 cm and occur randomly or are concentrated in layers (Fig. 30).

The sandstone facies is fine grained and for the most part structureless; where bedding is preserved, it is convoluted. Matrix-supported stringers or lenses of white conglomerate with angular, poorly sorted clasts ranging in size from coarse sand to pebbles occur locally.

The Church Rock Member is divided into blocky structures that increase in size upward and ultimately merge into columnar shapes. Where the blocky structures form columnar shapes, the concentration of nodules increases to almost 100% and their size decreases.

Halos, possibly marking roots, occur in the Church Rock Member in all areas with the exception of Little Bown Bench. Cylindrical trace fossils, formed by infilling of voids left by roots or burrowing animals, occur in all five measured sections. These trace fossils are most common near the top of the unit.

Figure 30: Nodule layer in the Church Rock Member in the Lizard Butte area. Layer is at the level of the bottom of the handle of the hammer (hammer is about 33 cm long).

Wingate Formation

The Jurassic Wingate Formation is a resistant cliff former that overlies the Chinle and caps the tops of all of the buttes and benches in the field area. It is composed of yellow, well sorted, medium-grained, quartz-rich sandstone with large-scale cross-beds. The contact with the underlying Church Rock Member is sharp, but does not appear erosional.

PALEOCURRENTS

Paleocurrent measurements were made on sedimentary structures including cross-bedding and pebble imbrication. In addition, the orientation of fossil wood fragments was measured in the Monitor Butte Member, and the orientation of fossil logs was measured in the Petrified Forest Member as possible indicators of paleocurrent.

Paleocurrent measurements made on cross-bedded sandstones were difficult to obtain because sandstones in the study area commonly are altered the point that sedimentary structures are difficult to interpret. Most paleocurrent measurements taken from cross-bedding are summarized in Table 3. These paleocurrent data are graphically represented by unit on rose diagrams in Figures 31, 32, 33, and 34.

At several locations only one or two paleocurrent measurements could be taken, or the paleocurrent could not be measured more precisely than a general direction. This was the case in the isolated sandstone bodies of the Upper Petrified Forest submember. Flow direction measured on cross-bedding is southeasterly for those particular sandstones.

Imbricated clasts were measured in the Wolverine conglomerate of the Bluewater Creek Member in the Wolverine Bench area. The paleocurrent data from these measurements are combined with data measured from cross-bedding and summarized in Table 3.

The orientations of wood fragments were also measured. In the Monitor Butte Member, wood fragments are up to 20 cm wide and 1 m long and commonly occur at the

Table 3: Summary of paleocurrent data (in degrees).

MEMBERS AND SUBMEMBERS

LOCATIONS	Shinarump	Bluewater Creek	Moss Back	Zebra Sandstone
Wolverine Bench	274.0	358.0	0.0	290.0
		315.0	30.0	305.0
		27.0		
		20.0		
		355.0		
	274.0	*215.0*	*15.0*	*297.5*
Badger Butte	220.0	80.0	25.0	
	290.0		183.0	
	225.0		148.0	
	312.0			
	66.0			
	220.0			
	320.0			
	236.1	*80.0*	*118.7*	
Circle Cliffs	200.0			
	200.0			
Bown Bench	350.0		250.0	30.0
	350.0		*250.0*	*30.0*
Lizard Butte	71.0		200.0	20.0
	71.0		*200.0*	*20.0*
Vector Mean	276.0	11.0	162.0	341.0

Bold green numbers indicate average value for the area.

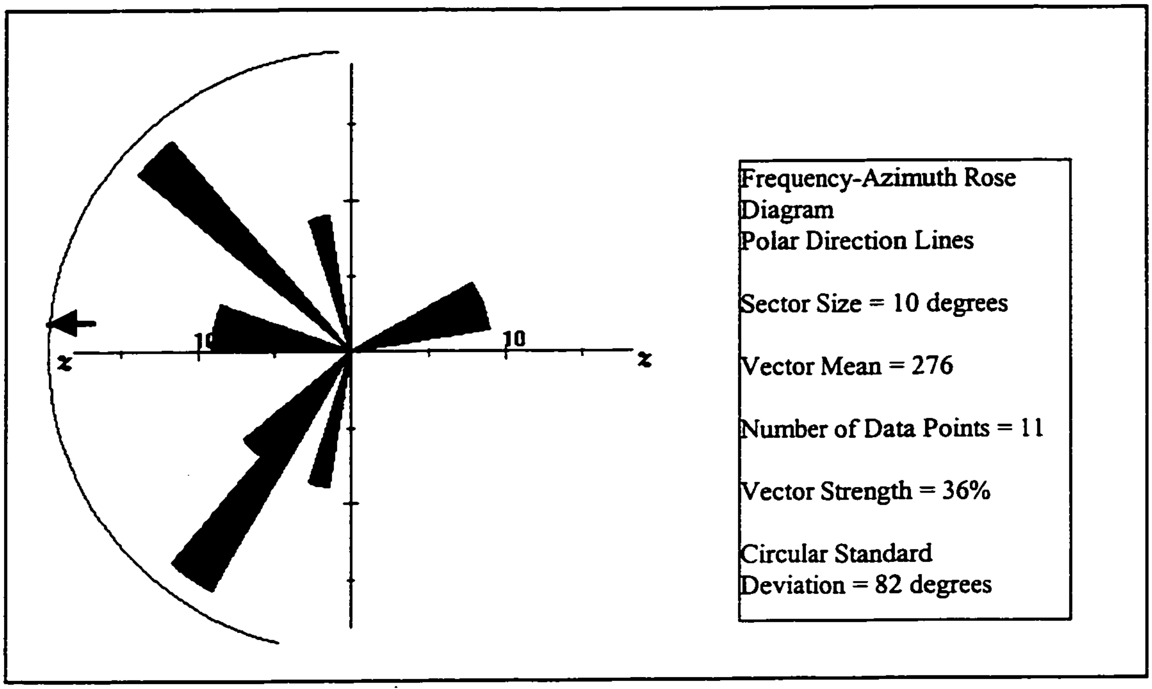


Figure 31: Shinarump Member paleocurrent directions. Arrow indicates vector mean.

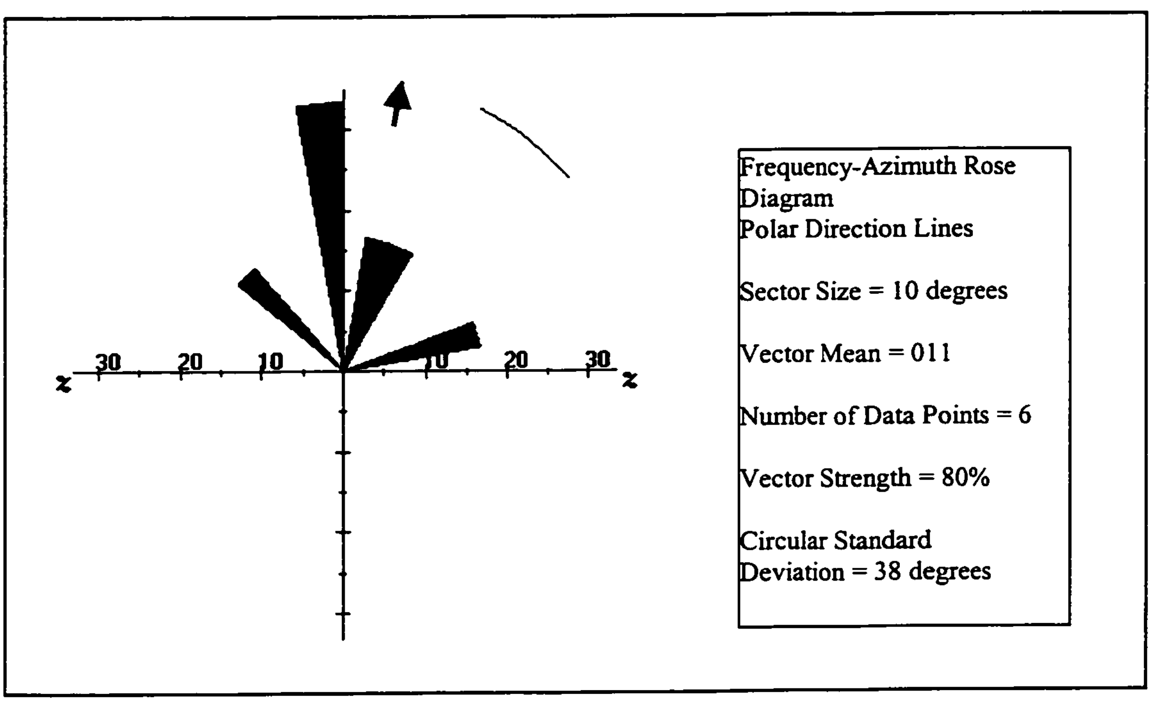


Figure 32: Bluewater Creek Member paleocurrent directions. Arrow indicates vector mean.

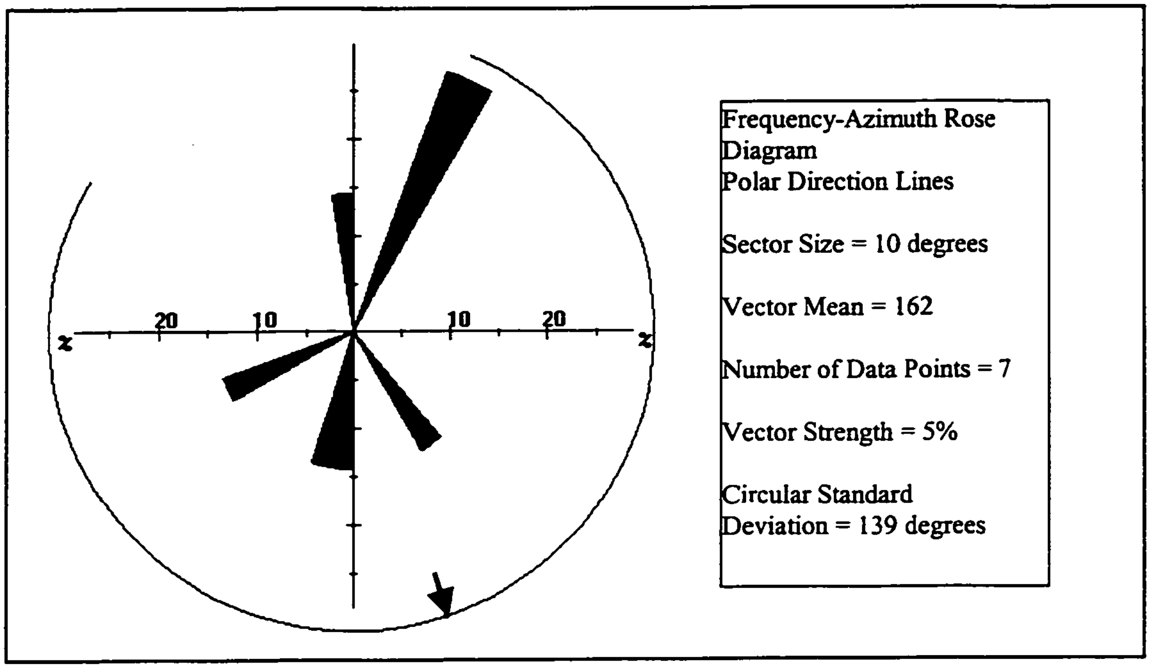


Figure 33: Moss Back submember paleocurrent directions. Arrow indicates vector mean.

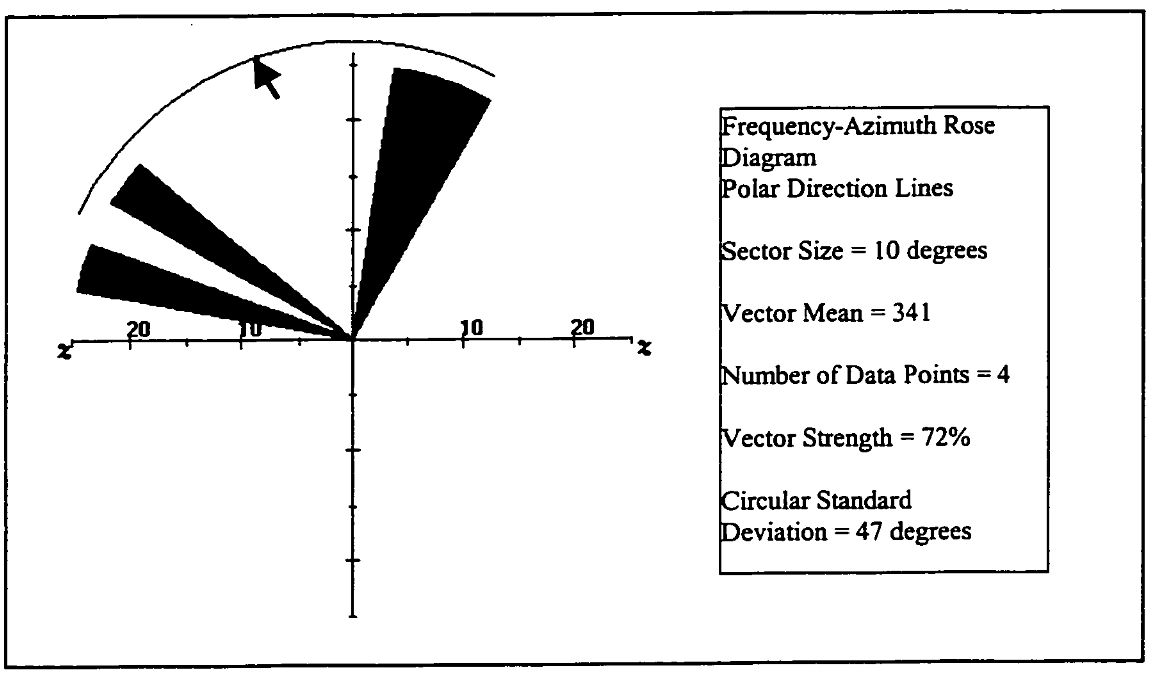


Figure 34: Zebra sandstone paleocurrent directions. Arrow indicates vector mean.

top of lateral accretionary sets, as in the Little Bown Bench area. Orientations of four fragments are N38°E, N15°W, N32°W, and N32°W. These fragments occur in a wood-rich layer about 3.3 m above the base of the Monitor Butte (Appendix). Ten meters higher, another log is present with an orientation of N80°W.

In the Petrified Forest Member, fossil log orientations were taken on trees in the Moss Back submember and the Zebra sandstone The general orientation of fossil trees in the Moss Back submember is northwest/southeast with a vector mean of 336° (N24°W) (Fig. 35). Logs measured at individual areas in the study area have a high degree of scatter, and only when all data from all locales are combined does a general orientation emerge. If these logs were deposited by stream processes then their orientation would reflect the paleocurrent that deposited them.

There are no apparent branches or roots associated with the logs in the Moss Back, although the prior location of rootballs can be determined by a flaring of the log structure. The bases of trunks, where identifiable, show a weak preferential orientation to the southeast (Fig. 36).

Only two fossil trees in the Zebra sandstone could be measured, they had orientations of N78°W and N60°E.

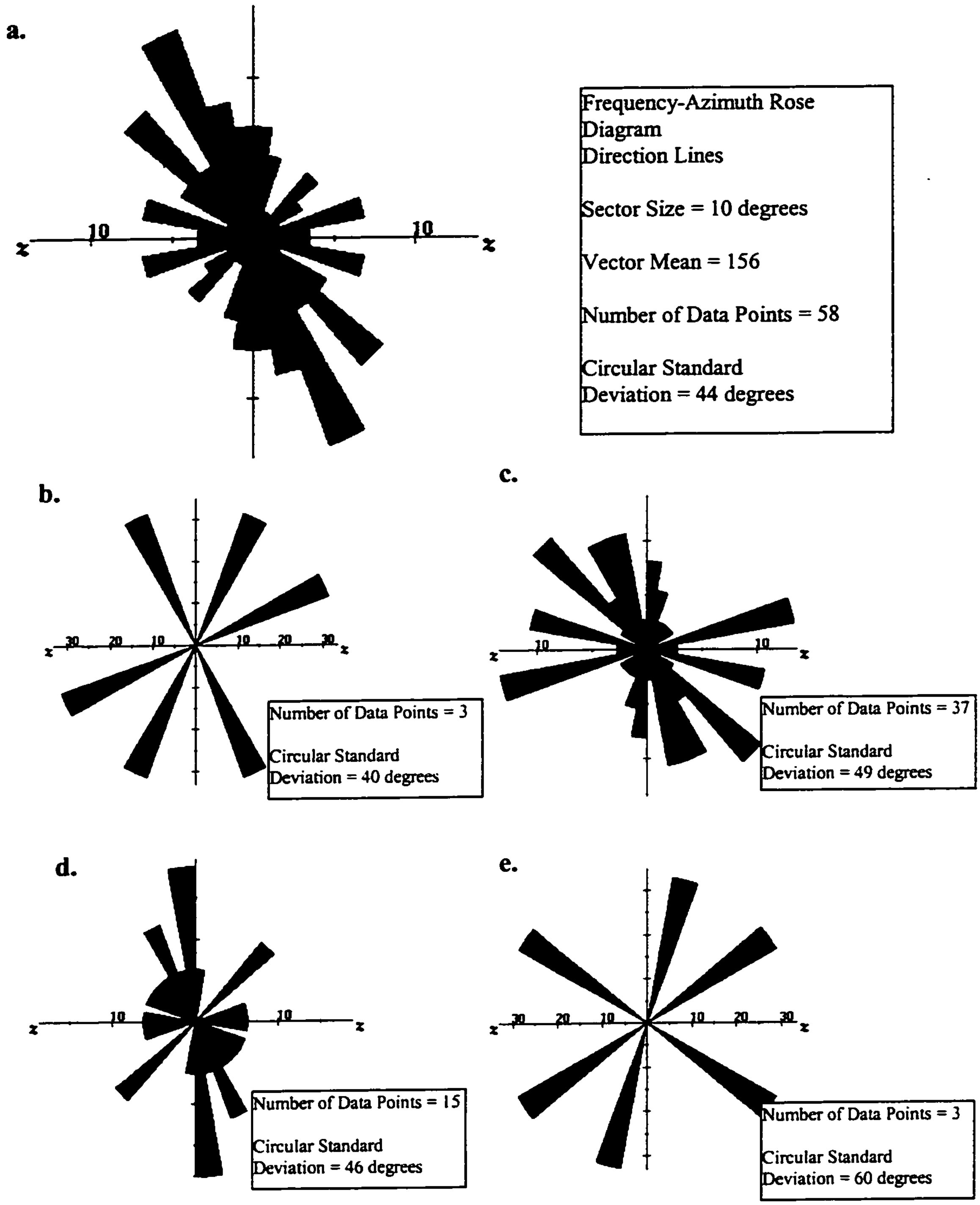


Figure 35. Orientations of fossil trees in the Moss Back submember. a, total measurements for all areas in the study area; b, the measurements taken in the Wolverine Bench area; c, the measurements taken in the Badger Butte area; d, the measurements taken in the Circle Cliffs area; and e, the measurements taken in the Lizard Butte area.

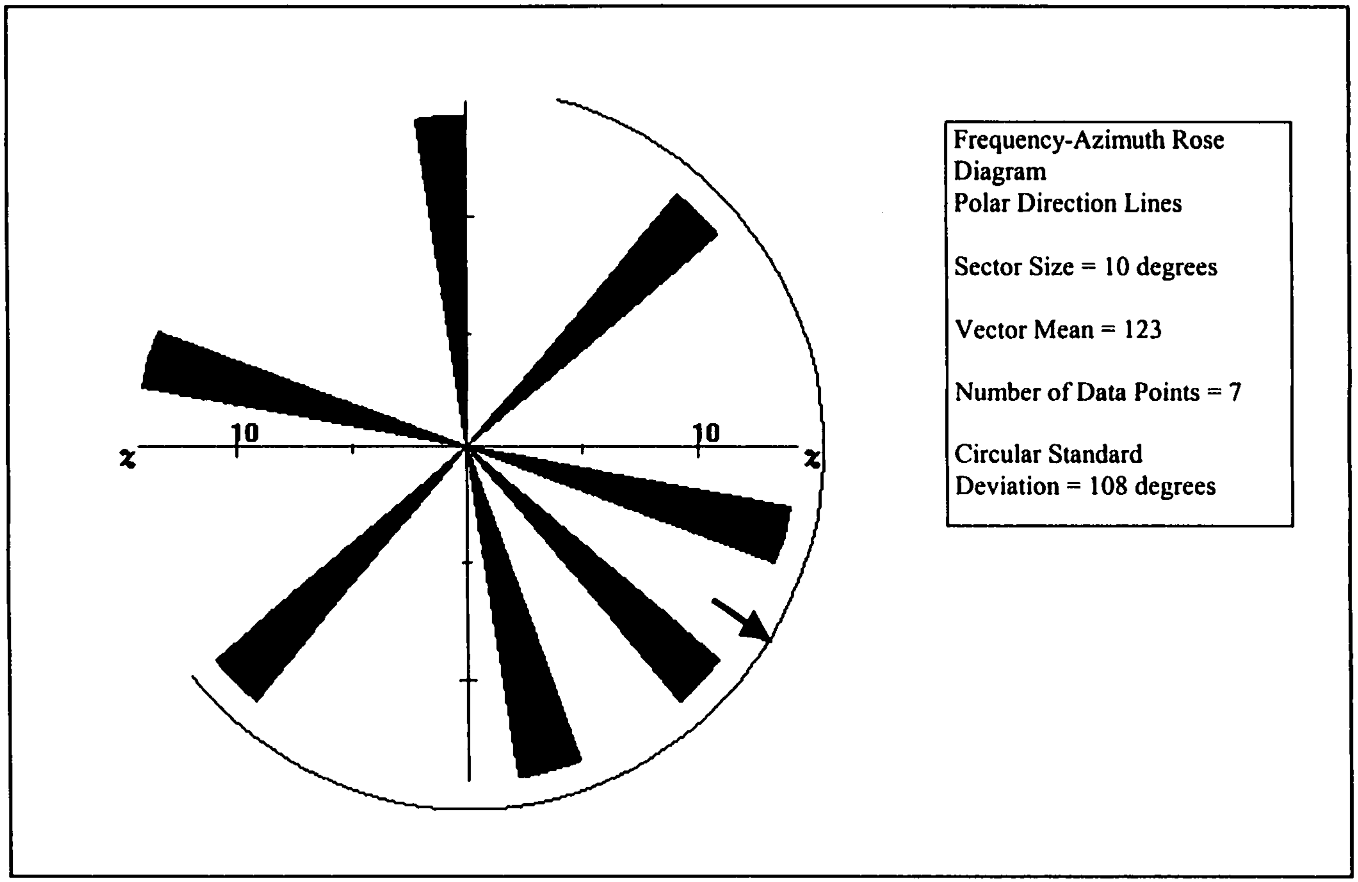


Figure 36: Orientations of remnant rootballs, Moss Back submember, Petrified Forest Member, Badger Butte area. Arrow indicates Vector Mean of root ball orientation. The trunk orientations seem to support inferred stream flow.

PETROGRAPHY

Sixteen samples taken from the Chinle Formation in the study area were studied. These are: one from the resistant brown sandstone bed that occurs in the lowermost Moss Back submember, five from the lavender sandstone in the center of the Moss Back submember, five from the red sandstone at the top of the Moss Back submember, and five from the Zebra sandstone. All of the sandstone samples are litharenites (Fig. 37) in the scheme of Folk (1968).

All samples plot in the recycled orogen provenance of the ternary diagram as indicated by Dickinson and Suczek (1979). The red, lavender, and resistant brown sandstones have similar compositions (Fig. 37). The Zebra sandstone is slightly richer in quartz and slightly poorer in polycrystalline lithic clasts than the remainder of the samples; however, the areas in which the populations plot overlap considerably.

The amount of quartz ranges from 32 to 73 % of the grains in the samples. Amounts of undulatory quartz generally exceed the amounts of nonundulatory quartz. Undulatory quartz makes up 24 to 79 % of all the quartz in the samples, with the average being 57 %. The amount of feldspar ranges from 1 to 11 %. Feldspar is mostly plagioclase but also includes trace amounts of microcline, which is present in all samples.

Polycrystalline lithic clasts make up 22 to 64% of the grains in the samples. These clasts consist of volcanic rock fragments and chert clasts of almost completely uniform crystal size (Fig. 38). The volcanics in the samples are largely devitrified into the

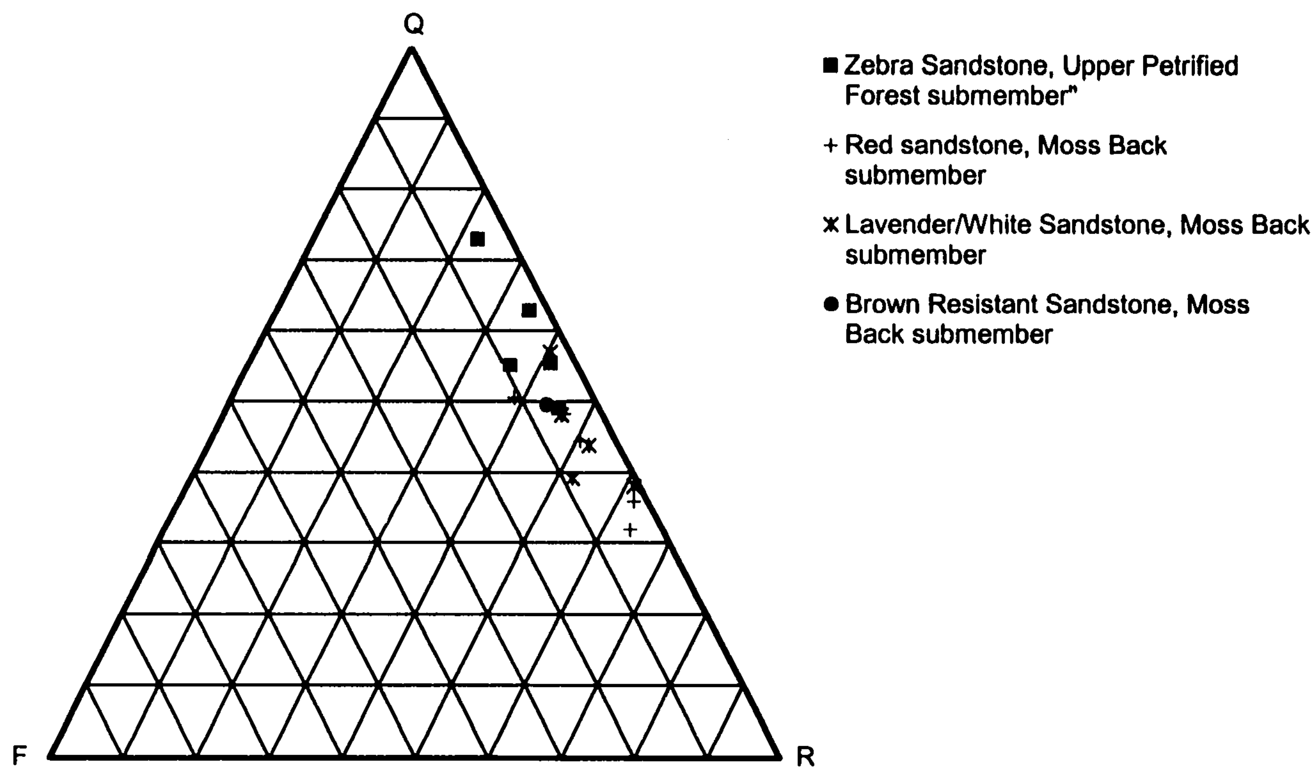


Figure 37. Ternary diagram of all sandstone samples (Q = total percentage of quartz, F = total percentage of feldspar, R = total percentage of lithics, including chert).

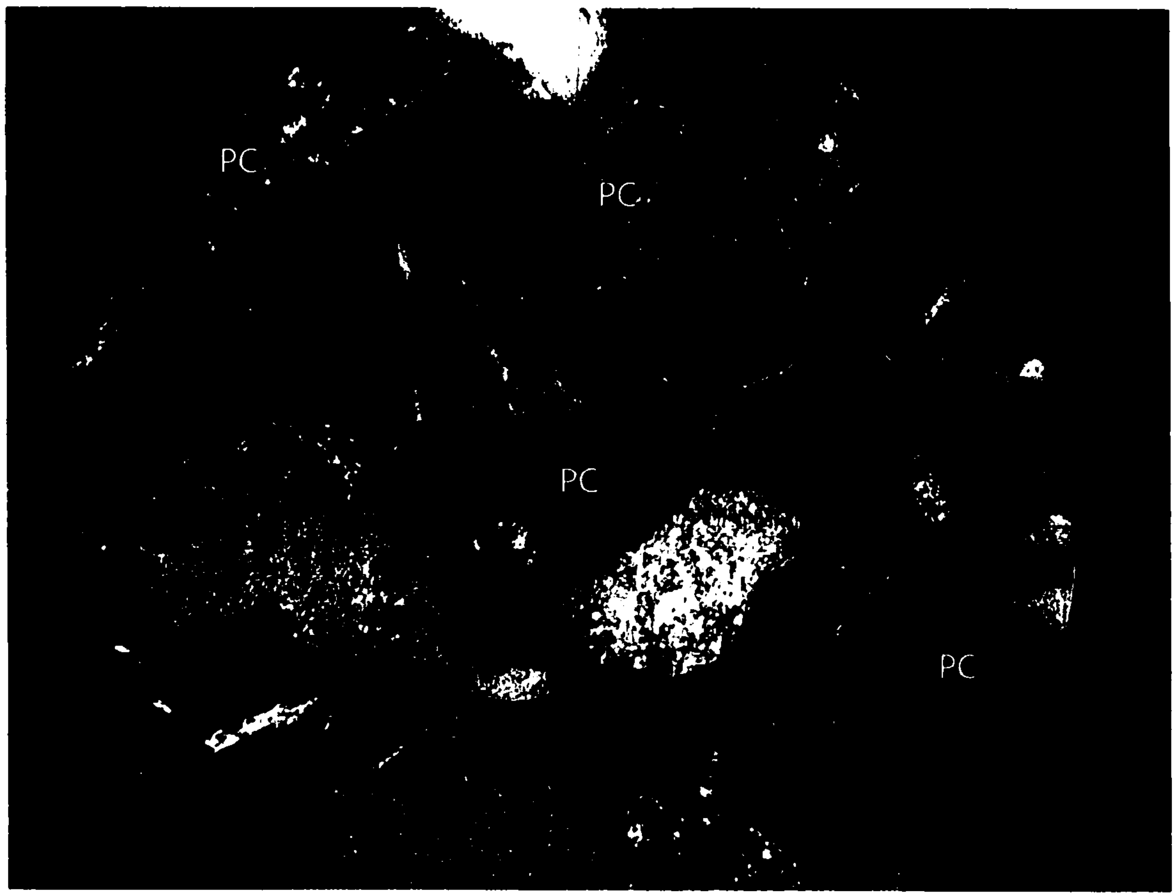


Figure 38. Polycrystalline clasts (PC) with roughly equally sized minute crystals in the Moss Back submember. Field of view is approximately 2.5 mm wide.

polycrystalline grains making identification difficult. Those grains that are clearly identifiable as volcanic in origin contain microphenocrysts of plagioclase feldspar.

The majority of the microcystalline grains are too fine grained to make a definite determination of whether they are volcanic clasts or chert. These grains are best classified as indeterminate microgranular grains according to the description of Boggs (1992).

The polycrystalline lithic grains are commonly bent along contacts with other grains, commonly partially enclosing adjoining grains to such a degree that the polycrystalline grains can be confused with matrix. The small grains in these deformed lithic clasts have a stretched appearance and are oriented parallel to the grain boundaries.

In nearly all samples, clear, colorless mica is present. Grains of mica are distorted, curving along boundaries between grains.

Grains in all samples are either angular or subangular, and there is a low degree of sphericity. Porosity is low in all samples with most grains in direct contact with adjoining grains. Where carbonate is present, it has replaced, to varying degrees, adjoining grains (Fig. 39). The polycrystalline lithics have been preferentially replaced as indicated by the numbers of polycrystalline grains that are partially replaced and by the remnant crystal structure preserved in the carbonate crystals.

The most conspicuous occurrence of calcite is in the red sandstone from the top of the Moss Back submember from the Circle Cliffs area, where carbonate has replaced over 70 % of the grains (Fig. 40). The sample is still 30% lithics; this sample probably was originally very lithic-rich.

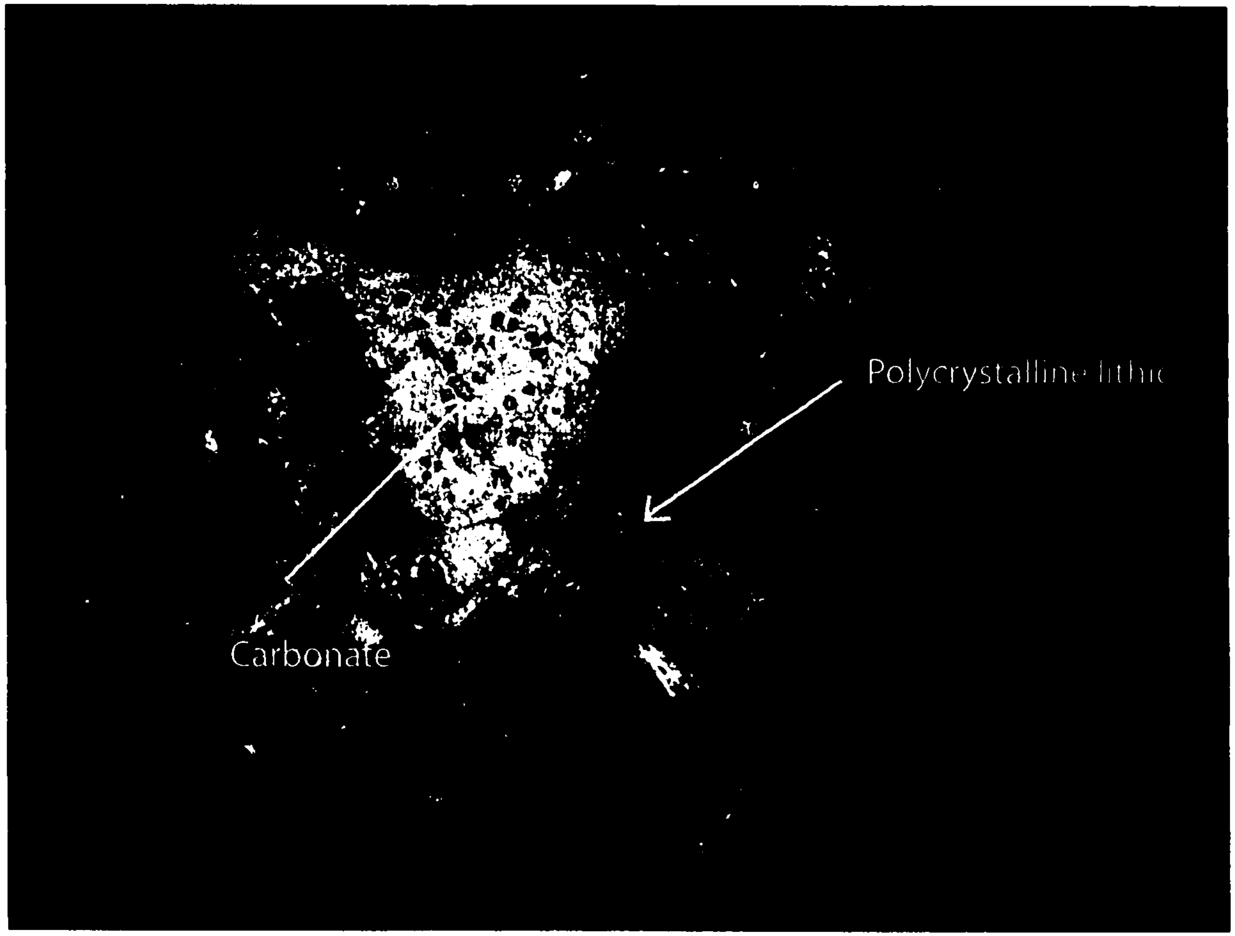


Figure 39. Polycrystalline clast partially replaced by carbonate in the Moss Back submember. Field of view is approximately 2.5 mm wide.

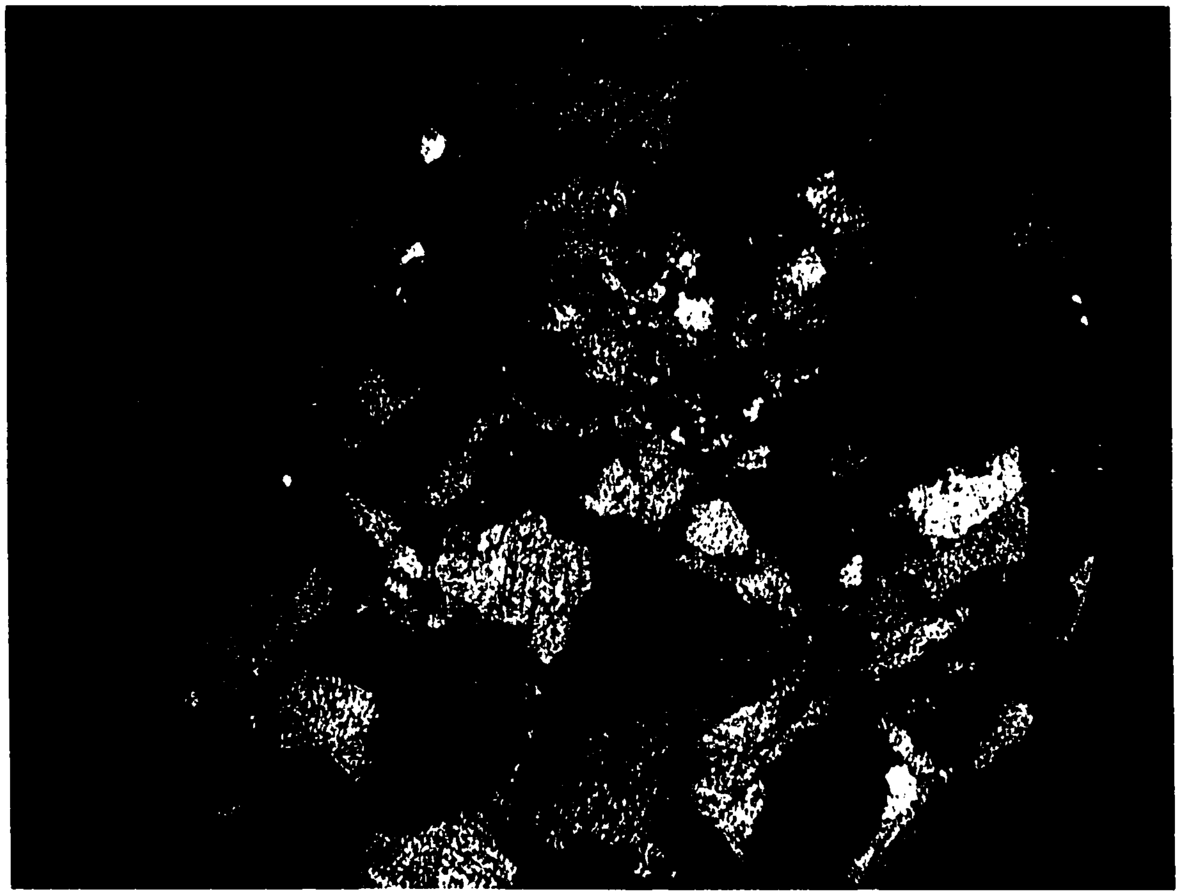


Figure 40. Carbonate replacement of grains in the red sandstone, Moss Back submember, Circle Cliffs area. Field of view is approximately 4 mm wide.

FOSSILS OF THE CHINLE

Fossils in the study area include fragments of and indications of both plants and animals. Fossils are concentrated in the Shinarump submember of the Shinarump Member, in the green siltstone facies of the Monitor Butte Member, in the sandstone facies of the Bluewater Creek Member, and in the Moss Back submember and Zebra sandstone of the Petrified Forest Member.

Permineralized Trees

The most abundant fossils are the permineralized trees present in the Moss Back submember and the Zebra sandstone. The Moss Back submember contains the most abundant assemblage of permineralized logs. Fossil logs commonly lie at angles to the horizontal. The direction of tilt is variable and the cause is not readily apparent from the sediment surrounding the logs. Logs range from 15 cm to 1.5 m in diameter and 7.0 to 25.0 m in length; due to fracturing, original lengths are never preserved.

The fossil trees in the Zebra sandstone appear similar in size to those in the Moss Back, although they are much fewer in number. Only two fossil trees were found in place in the Zebra sandstone so that their orientations could be measured.

The logs in the Moss Back submember and Zebra sandstone are commonly encased in cross-bedded sandstone (Fig. 41) in which the cross-bedding is not deflected around the location of the log. Logs are broken normal to their length by planar fractures (Fig. 42). They appear to have excellent preservation of external structure, although the

Figure 41. Permineralized wood in cross-bedded sandstone in the Moss Back submember, Little Bown Bench area. Rock hammer is about 33 cm long.

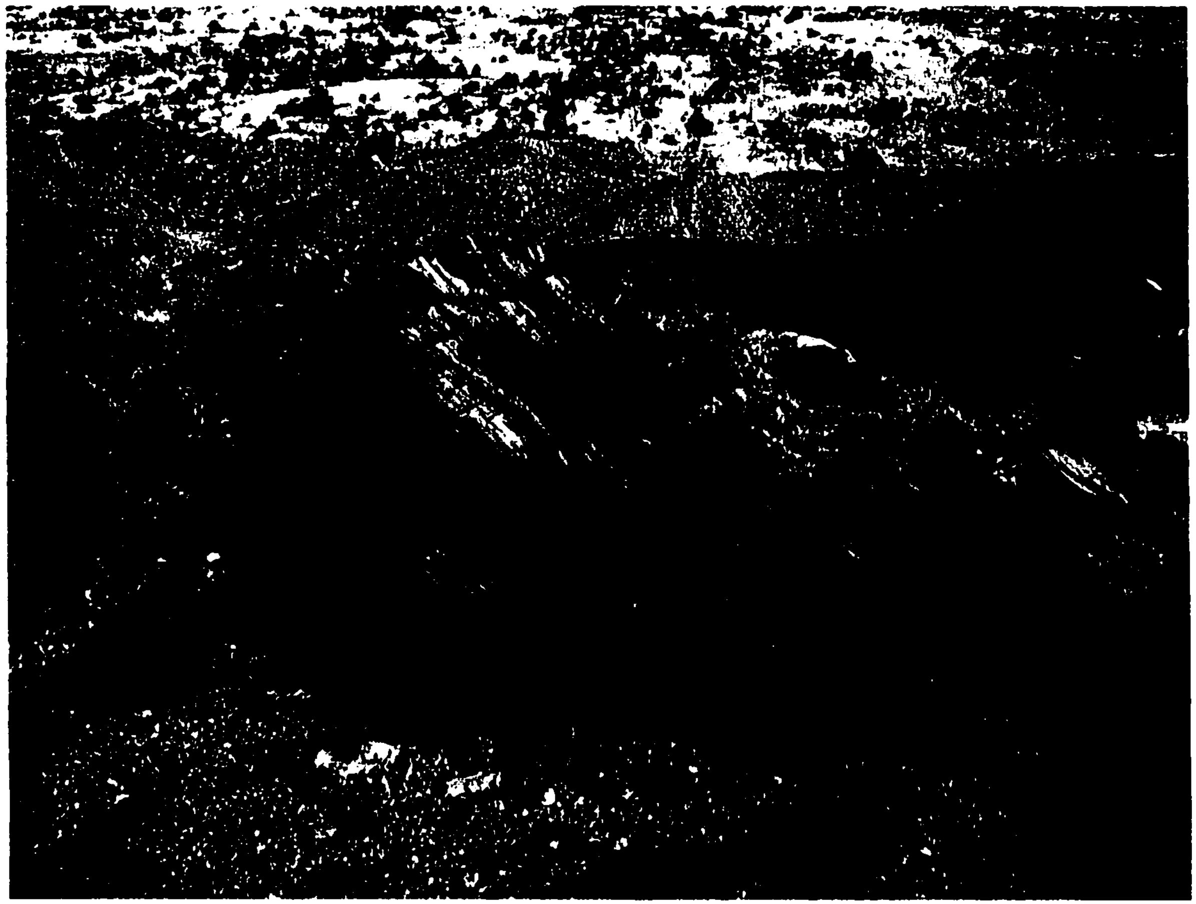


Figure 42. Log in the Badger Butte area showing typical planar fractures. Rock hammer is about 33 cm long.

outermost layer cannot be verified as bark. The internal structure is generally poorly preserved with visible structures differing from tree to tree. The main internal features appear to be regularly spaced growth rings (Fig. 43). The color of the permineralized wood in the field area, both externally and internally, is generally dark, almost black (Fig. 43).

Some trees contained voids prior to burial; these voids are now filled with dogtooth-spar calcite. In several outcrops, the centers of the trees are filled with sandstone similar to that which encases them. Those trees that had been hollowed out before burial commonly appear oblate with the longer axis parallel to bedding, as if they had been crushed.

There are no apparent branches or roots associated with the logs, although the prior location of rootballs can be determined by a flaring of the log structure. The bases of trunks, where identifiable, show a weak preferential orientation (Fig. 36).

Carbonized Leaves and Wood

In addition to the permineralized trees, carbonized leaves and carbonized wood are present. Carbonized wood occurs in the Shinarump Member, and carbonized leaves occur in resistant lenses in the siltstone facies of the Monitor Butte Member and in the sandstone facies of the Bluewater Creek Member. The pinnae of the carbonized leaves in the Monitor Butte have slightly divergent venation, are rectangular to oblong in shape, are longer than wide, are contracted in the upper and lower basal angles, and have symmetrical bases (Fig. 44). The ends of the pinnae are rounded. They are connected to

Figure 43. Log in the Badger Butte area showing distinctive gray to black color and internal structures appearing to be growth rings. Pencil is about 14 cm long.

Figure 44. Carbonized leaf from the pale-green siltstone facies of the Monitor Butte Member in the Badger Butte area.

the rachis in an apparent equitant arrangement (connected at the center of the leaf as measured across its width and overlapping the rachis), occur alternately on the rachis, and range in width from 9.2 mm to 15.1 mm. The lengths of the pinnae are difficult to measure because most are broken or are difficult to identify as whole; complete pinnae have an average length of 67 mm. The rachii range in width from 3.3 mm to 5.7 mm. No whole leaves were observed.

The pinnae of the carbonized leaves in the Bluewater Creek are similar to those in the Monitor Butte. They have unrecognizable venation, are oblong in shape, are longer than wide, have unrecognizable basal angles, and have symmetrical bases. The ends of the pinnae are rounded. They also occur alternately on the rachis, range in width from 6.0 mm to 11.4 mm, and have a mean length of 39 mm. The true lengths of the pinnae are difficult to measure because most of the pinnae are broken and/or it is difficult to determine whether or not they are whole. The width of the rachii ranges from 2.1 to 3.6 mm. Whole leaves range in width from 44.8 mm to 91 mm and in length from 184.1 mm to 200 mm, and are commonly curved toward their ends. The leaves are randomly oriented and occur on bedding surfaces.

Trace Fossils

Animal burrows are recognizable in the Monitor Butte Member and in the Bluewater Creek Member. In the Monitor Butte Member, burrows are horizontal with widths of 0.5 to 1 cm and lengths of 3 to 5 cm. In the Bluewater Creek Member, burrows are vertical with widths of 0.5 to 1 cm and lengths up to 10 cm (Fig. 45). Root traces are

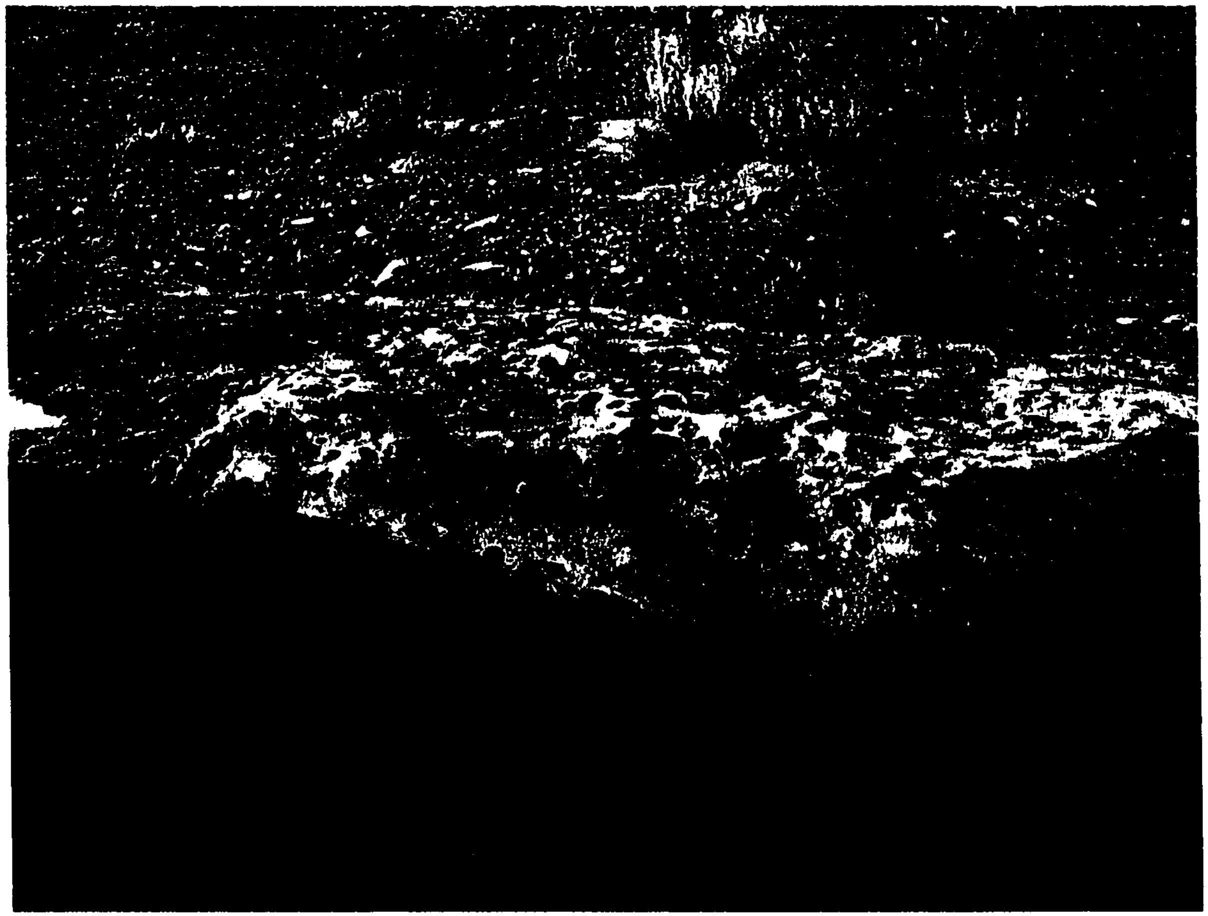


Figure 45. Burrows in the Bluewater Creek Member in the Badger Butte area (pencil is about 14 cm long).

present primarily in the upper part of the Chinle where they are associated with soil horizons.

Animal Fossils

Vertebrate bones have been discovered in the Moss Back submember at two sites within the field area. The bone fragments have a slight bluish color and opaline luster and occur in isolated accumulations that contain too few fragments (Fig. 46) for identification. The bones evidently were fragmented in place because all fragments preserve sharp edges. The surfaces of the bone fragments at one site are pitted with elongate grooves that taper in one direction. The interior of the bones at both locations has only partial mineral infilling.

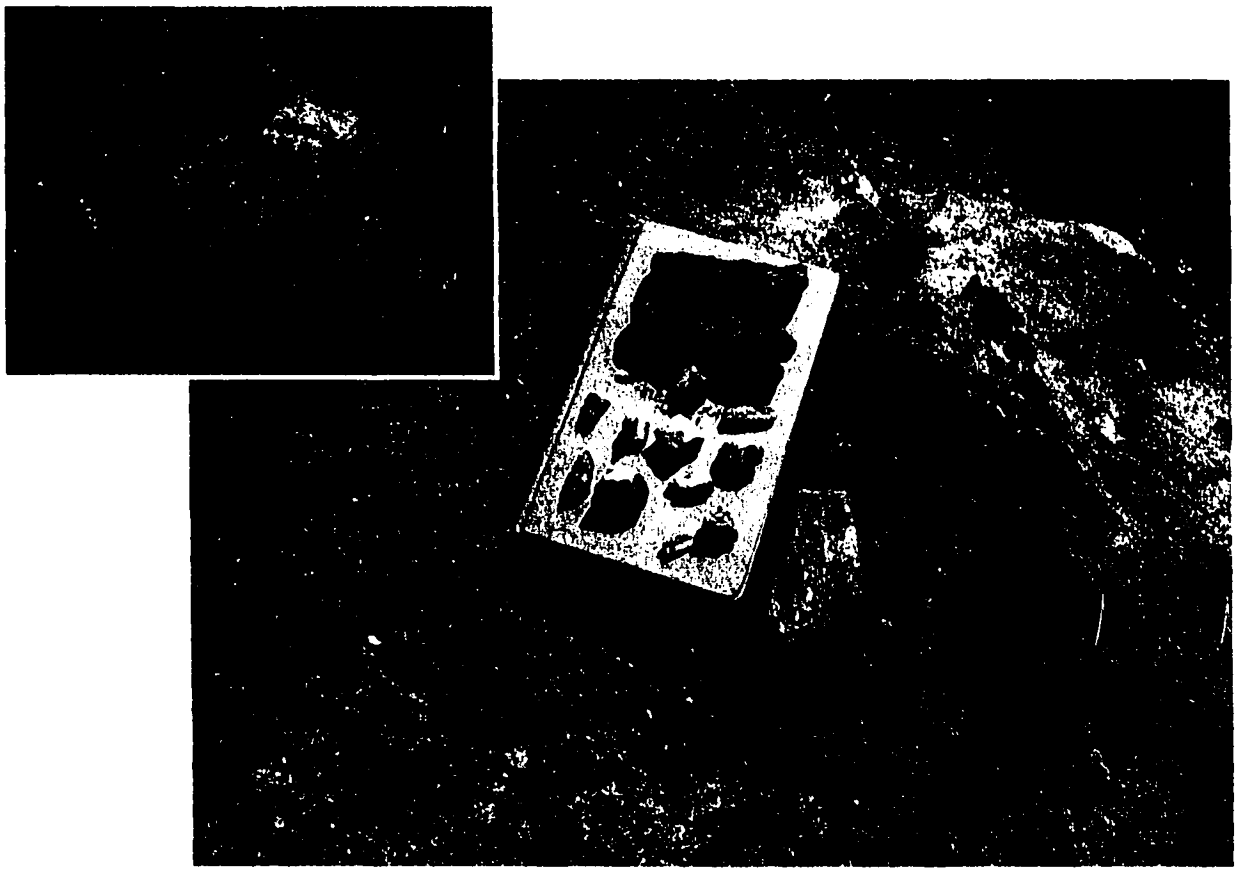


Figure 46. Vertebrate bones from the Moss Back submember of the Petrified Forest Member in the Badger Butte area. Inset shows bones from the Lizard Butte area. Notebooks are 19 cm long.

INTERPRETATIONS

The mudstone, sandstone, and conglomerate of the Chinle Formation are interpreted to have been deposited in fluvial and lacustrine settings on the basis of sedimentary structures and facies relationships. The sandstones in the Shinarump Member are bedded in angular, wedge-planar and sinusoidal and parabolic, tabular-trough cross-beds, contain asymmetric ripple marks, and contain lateral accretion surfaces, all of which typify fluvial deposits (Miall, 1996). In the interbedded sandstone and siltstone informal submember of the Monitor Butte Member, cross-bedded sandstone is interbedded with siltstone with symmetrical ripple marks. The presence of such marks and the presence of well preserved terrestrial leaves in fine-grained rocks indicate a lacustrine environment. The imbricated limestone-pebble conglomerate and ripple-laminated sandstone of the Bluewater Creek Member fill channels cut into the Monitor Butte Member, indicating a return to fluvial deposition. The overlying Petrified Forest Member is dominated by mudstone with rare conglomerate and sandstone bodies. These bodies have erosional bases and directional sedimentary structures that record the persistence of fluvial processes. The Moss Back submember contains conglomerate and parabolic-trough cross-bedded sandstone that fills channels cut into the Lower Petrified Forest submember. Above the Moss Back submember, isolated sandstone and conglomerate bodies have erosional bases and are planar cross-bedded. The Zebra sandstone has sinusoidal, parabolic, and angular, wedge-planar cross-beds and horizontal beds filling channels cut into the Upper Petrified Forest submember. The Owl Rock and Church Rock members contain trace fossils inferred to be root traces or burrows that indicate continental deposition. The depositional agent was likely a river; therefore, evidence of fluvial processes persists throughout the Chinle Formation.

Paleosols

The mudstones of the Monitor Butte, Bluewater Creek, Petrified Forest, Owl Rock, and Church Rock members are interpreted to have been deposited by flood events on interchannel areas and floodplains because of their association with stream deposits. In this study, these mudstones are interpreted as having been altered into paleosols based on presence of soil structures and fabrics, presence of other soil features such as evidence of roots and burrows, and evidence of soil horizonation.

Soil microstructures and fabrics in the study area include peds, the blocks into which soils are structurally divided, and clay particle alignment. In the study area, peds are predominantly angular to subangular and blocky in appearance (Table 2). These peds dominate the clayey mudstone facies of the Monitor Butte Member, the Bluewater Creek Member, and most of the Petrified Forest Member. The Owl Rock Member and Church Rock Member contain peds that are subangular blocky and columnar.

Peds form when soil shrinks and swells with alternating wetting and drying (Retallack, 1990; Therrien and Fastovsky, 2000). Slickensides present on peds (Fig. 47) indicate shrinking and swelling in response to changing water content (Retallack, 1990; Therrien and Fastovsky, 2000).

Figure 47. Slickensides on a ped from the Upper Petrified Forest submember, Lizard Butte area.

Both carbonate and silica nodules indicate that water evaporated from the soil during at least part of the year; concentric layers in those nodules indicate a seasonal climatic regime (Therrien and Fastovsky, 2000). Nodules are common in paleosols in the Monitor Butte through Church Rock members of the study area with concentric layers occurring in nodules in the Monitor Butte Member. This indicates seasonality as early as the time of deposition of the Monitor Butte Member.

Nodules in the Chinle Formation can be shown to have formed during soil formation rather than during later diagenesis through at least two lines of evidence. First, nodules in some outcrops appear at a specific depth beneath the paleosol surface indicating that they formed at the wetting front at the time of soil formation. Second, nodules occur as pebbles in fluvial conglomerates that overlie soils in the Monitor Butte and Petrified Forest members, showing that nodules formed prior to deposition of the conglomerates.

Various attributes of paleosols give valuable information about the paleoenvironment, length of subaerial exposure, and climate at the time of their formation. Red and purple soils probably are the result of concentrations of iron oxides, particularly hematite, along with a low content of organic matter, recording well drained, oxidizing conditions. Green coloration indicates water saturation, poor drainage, and reducing conditions (Therrien and Fastovsky, 2000).

Mottling in the paleosols indicates that the floodplain may have been periodically poorly drained (Retallack, 2001). The red to green vertical transitions in mottling color seen throughout the study area may be the result of surface water gleying caused by impermeable, clay-rich soil that periodically kept stagnant water near the surface, allowing decomposition and reducing conditions to occur. In such circumstances, the uppermost part of the soil would be saturated by reducing water creating a solid green layer. The reducing surface water that percolated down into the underlying soil followed root traces, cracks, and possibly burrows creating more scattered mottles (Retallack, 1990).

The creation of mottles by reduction rather than by carbonate accumulation is indicated by the uniformity of texture and cementation within the mottled mudstones as well as by the absence of carbonate in the mottles. An exception to this occurs in unit 15 of the Petrified Forest Member in the Wolverine Bench (Appendix), where the mottles are better cemented and are more hygroscopic than the surrounding mudstone.

Drab halos, characterized by elongate areas of bluish-green color extending into paleosols, suggest the presence of roots in growth position. They are differentiated from mottles by their downward branching shape. Possible roots in growth position in the Petrified Forest, Owl Rock, and Church Rock members in the field area suggest that paleosols within these members were subaerially exposed and stable long enough for plant colonization.

Climate can be interpreted through multiple lines of evidence recorded in paleosols including soil horizon, microstructures, fabrics, and other features. Soil horizon differentiation can be difficult. Periodic depositional events can deposit fresh sediment on top of the soil, and pedogenic alteration can progress across the boundary between the new and the old soil. A horizons (Table 1) can be particularly difficult to identify because organic matter is destroyed under oxidizing conditions (Blodgett, 1988).

The rarity of A horizons in the study area is typical in well developed clayey soils (Retallack, 1990) and is consistent with what is seen in similar deposits across the Colorado Plateau (Blodgett, 1988). Where A horizons are present, they do not show preferential darkening or evidence of eluviation (Table 1). A horizons occur in the Circle Cliffs and Wolverine Bench areas. In the Circle Cliffs area in the Lower Petrified Forest submember, a C horizon (older sediment weathered to a lesser degree than an A, E, B, or K horizon) grades vertically upward into an A horizon (recognized by the presence of granular peds). In the Wolverine Bench measured section in the Lower Petrified Forest submember, there are several Ac horizons (Appendix).

Blodgett (1988) discussed the absence of A horizons in the Dolores Formation in southwestern Colorado, giving four possible reasons for their absence. First, organic material may not have accumulated in quantities large enough or of the appropriate type to result in melanization. Given the high number of plant fossils, particularly carbonized leaves and permineralized wood in the field area, this seems unlikely. Second, surficial accumulations of organic matter may have been lost during burial and subsequent oxidation of the paleosol. Third, eluvial horizons may have been present but not recognized. Finally, epipedons are commonly subject to removal by erosion. Any one or all of these last three processes may have acted upon the soils seen in the field area.

In the Monitor Butte, Bluewater Creek, Petrified Forest, Owl Rock, and Church Rock members, B horizons (Table 1) are recognized based on enrichment in clay and carbonate in the form of nodules (Appendix). The dominance of Bt (Table 1) horizons in the Monitor Butte, Bluewater Creek, and Petrified Forest members indicates that soil formation took place under forest flora in warm humid climates. The dominance of Bk horizons in the Owl Rock Member is recognizable by enrichment in carbonate (Table 1) and indicates that soil formation took place under arid to semiarid conditions (Retallack, 2001). The dominance of Bn horizons, recognizable by the formation of columnar peds (Table 1), in the Church Rock Member indicates semiarid conditions (Retallack, 2001).

Most soils in the study area can be classified as Vertisols, Entisols, Aridisols, and Alfisols (Retallack, 2001). The mudstone facies of the Monitor Butte Member, Bluewater Creek Member, and the Lower and Upper Petrified Forest submembers include slickensides, high clay content, and carbonate nodules. Based on these features, these mudstones can be identified as Vertisols, uniform, thick, clayey soils that form in seasonally subarid to subhumid conditions (Troeh and Thompson, 1993; Hasiotis et al., 1998; Retallack, 2001). When the soil classifications of the paleosols in the Monitor Butte Member, Bluewater Creek Member, and the Lower and Upper Petrified Forest submembers are combined with the information provided by the horizons recognized within them, a warm humid climate with seasonal periods of drying is indicated.

In the red sandstone from the top of the Moss Back submember from the Circle Cliffs area, carbonate has replaced over 70 % of the grains (Fig. 40). Because original structures and bedding have not been disrupted in this paleosol, it is best described as an Entisol (Retallack, 2001).

The Owl Rock Member has a high degree of calcite, silica, and dolomite cementation, which accounts for its distinctive stepped appearance (Fig. 48). Due to the high degree of cementation by carbonate and large numbers of carbonate and silica nodules, soils in the Owl Rock Member should be classified as Aridisols, soils with shallow calcareous and/or argillic horizons commonly formed by the concentration of nodules (Retallack, 2001). Aridisols form when seasons with enough moisture for plant growth last less than 3 months (Retallack, 2001). This member also displays the more subdued coloration typical of calcareous paleosols (Retallack, 2001).

The Church Rock Member exhibits a columnar morphology (Fig. 49), and there are indications of roots and possibly burrows in this uppermost unit. It meets the requirements of a Xeralf Alfisol, which typically has a red color and forms in areas with long dry seasons and warm climates such as in the Mediterranean region (Retallack, 1990). It is possible, however, that the dark red color of the Church Rock does not reflect depositional conditions, but instead reflects post-depositional conditions.

Biological activity is a key soil forming process; therefore, the presence of paleosols indicates a high level of biological activity. The formation of soil destroys fossils (Retallack, 2001), however, explaining how a low diversity of fossils is preserved in the study area despite a high level and diversity of biological activity.

Fossils

During the time of deposition of the Chinle Formation, the environment not was conducive to the preservation of fossils. The few fossils in the study area include petrified

Figure 48. Well cemented cliff in the Owl Rock Member in the Badger Butte area (cliff is about 2.5 m high).

Figure 49. The Church Rock Member in the Circle Cliffs area, showing columnar morphology (outcrop is 4.5 m high).

wood, coalified leaves, and vertebrate bones, with the highest concentration of fossils occurring in the lower Chinle Formation.

Plant Fossils

Plant fossils in the study area include logs, which may be either carbonized or silicified, and leaves that are exclusively carbonized.

Logs. Permineralized logs are the most apparent fossils in the study area, occurring in great numbers in the Moss Back submember, and rarely in the Zebra sandstone of the Petrified Forest Member. Carbonized logs occur in much smaller amounts in the Shinarump Member. Although these trees are not identified in this study, they are probably *Araucarioxylon,* the most common fossil tree found elsewhere in the Chinle Formation (Sid Ash, pers. comm., 2001). This genus is most closely related to the modern Chilean Monkey Puzzle Tree and the Norfolk Island Pine of the South Pacific. Both of these modern trees are tropical to subtropical in habitat and grow to 3 m in diameter and 61 m in height (Harris et al., 1997). In this study, trees with diameters up to 1.5 m and lengths up to 25 m were measured.

Permineralized wood is not ubiquitous in the Moss Back submember of the Petrified Forest Member and is rare in the Zebra sandstone. Stewart et al. (1972a) found no petrified wood in the Moss Back submember in the Horse Canyon area of the Grand Staircase-Escalante National Monument. The lack of petrified wood there indicates that either no trees were being deposited or conditions after deposition were not favorable to the permineralization of wood. There is no evidence that the depositional and post-depositional environments in the Horse Canyon area were different than elsewhere, suggesting that trees were simply not deposited there.

Log Orientation. The general orientation of logs was determined for the Moss Back submember and the Zebra sandstone. In the Moss Back submember it is N24°W (Fig. 35). Although the paleocurrent measurements for the Moss Back have too low of a vector strength to be truly useful, the generally northwest orientation of these logs is subparallel to the northwest paleocurrent measured from cross-bedding in the Shinarump Member and Zebra sandstone (Figs. 31 and 34) and to the northeast paleocurrent measured in the Bluewater Creek Member (Fig. 32). Paleocurrent measurements for the Zebra sandstone indicate a direction of N19°W (Fig. 34), and the orientations of the two measurable logs were oblique to this. According to Demko (1995), the orientation of logs subparallel to the paleocurrent suggests deposition along the channel margins; in mid-channel deposits they tend to be oriented oblique to the paleocurrent. There also is a large degree of scatter in the orientation of logs in Moss Back submember in the study area (Fig. 35), which is expected in mid-channel deposits (Demko, 1995). Because of the high standard deviation in the measurements, however, any interpretations would be highly speculative.

The degree of transportation these trees experienced cannot be determined. Bark cannot be identified with certainty, but the lack of branches and roots indicates that some transportation did take place.

The planar fractures cutting across the width of the trees occurred after preservation. Because the majority of the trees have experienced some degree of lateral fracturing, post-depositional displacement of the trees results in their dismemberment. This agrees with what Harris et al. (1997) reported in the Petrified Forest National Park and acts as an important constraint on the interpretation of original depositional position of the trees. For instance, trees measured for orientation in this study are not dismembered, although they are highly fractured, indicating that they are resting in the orientation in which they were preserved.

Log Preservation. Most of the wood in the Chinle Formation has been preserved through silicification, although the wood in the Shinarump Member experienced carbonization rather than silicification.

In the logs preserved through silicification, preservation of the internal structures of the logs is generally poor. The only internal features that are still discernable are apparently regularly spaced rings (Fig. 43), possibly annual growth rings caused by seasonal fluctuations in water supply and weather. The identity of these rings as annual growth rings, however, cannot be confirmed because the cellular structure has not been preserved in the samples taken for this study.

If the rings seen in the study area are not growth rings, the climate at the time of their deposition still could have been seasonal. Their possible mid-channel location and the absence of roots and branches indicates that these trees were transported some distance before deposition. They may have been carried from more humid uplands to their place of deposition on a more seasonal alluvial plain, a theory put forth by Harris et al. (1997).

Trees with hollow centers now filled with dogtooth-spar calcite or sandstone were likely rotten before deposition. Their oblate shapes reflect partial crushing of the logs either during deposition or during preservation.

Whether wood is silicified or not depends on the burial environment. Previous work indicates that silicification requires rapid burial to prevent decomposition and continual saturation with silica-enriched groundwater. The woody structure is then slowly replaced by silica derived from surrounding groundwater (Chronic, 1986; Harris et al., 1997).

Silicification occurs at earth surface pressures and temperatures and within the silica concentration range typical of most ground and surface waters. Silicification requires a continuous supply of silica in solution. The source for the silica for permineralization in the study area was likely volcanic ash from a string of volcanoes located to the west and south as suggested by various workers (Stewart et al., 1972a; Blakey and Gubitosa, 1983; Dubiel and Hasiotis, 1994; Therrien et al., 1999).

Iron mineralization associated with permineralization has two forms, iron oxide (hematite) and iron-hydroxide (goethite and lepidocrocite). Hematite often acts as the primary agent of preservation and is later joined by a second mineral such as pyrite, which precipitates at the Eh and pH conditions associated with decaying tissues (Buurman, 1972). The presence of these secondary minerals indicates that the sample was mineralized in an environment that went from oxidizing to reducing conditions

(Buurman, 1972). Although hematite tends to preserve structures, recrystallization may ultimately result in their degradation (Buurman, 1972) as is seen in the poor preservation of internal structures in logs in the study area. Minerals containing Mn and Fe are linked to darker coloration (Buurman, 1972) and could explain the dark color of the wood in the study area.

The time required for mineralization is dependent on the concentration of solutes and the pH of the groundwater in which they are carried. Initial precipitation may occur rapidly, preserving cellular details. Secondary mineralization may take longer and results in a loss of fine detail (Sigleo, 1978b). Because there is generally poor preservation of detail in wood in the study area, it is likely that secondary mineralization occurred.

The wood in the Shinarump and Monitor Butte members experienced carbonization rather than silicification. The excellent preservation of internal structure in the carbonized wood indicates that only distillation occurred. Their occurrence as fragments and their association with poorly sorted gravel lenses indicates that they were deposited in lag deposits (Miall, 1996).

<u>Leaves</u>. Carbonized leaves from the Bluewater Creek and Monitor Butte members have slightly divergent venation, are rectangular in shape, are longer than they are wide, are contracted in the upper and lower basal angles, and have symmetrical bases. These characteristics are diagnostic of *Zamites* (Tidwell, 1998). The apparent equitant connection of the pinnae slightly above the lateral margin of the rachis and the alternate

attachment of the pinnae on the rachis support the identification of these leaves as *Z. powelli* (Ash, 1975).

Zamites powelli is one of the most common fossil leaves in the Lower Chinle Formation with documented occurrences in western New Mexico, Arizona, Utah, and in the correlative Dockum Group of eastern New Mexico, western Texas, and western Oklahoma (Herrick et al., 1999). The leaves are common outside the area of this study in the Sonsela Sandstone (laterally equivalent to the Moss Back submember), the Lower Petrified Forest submember, and the Monitor Butte and Shinarump members (Daugherty, 1941; Ash, 1975; Herrick et al., 1999).

Animal Fossils

Animal bones in the Chinle Formation are likely from *Buettneria perfecta* or *Apachesaurus gregorii*, both members of the family Metoposauridae (Hunt et al., 1993b). *Buettneria,* a relatively large animal, was water dwelling, required an open-water habitat, and is therefore found in fluvial channel and lacustrine deposits alongside semiaquatic and aquatic faunas (Hunt et al., 1993a; Hunt et al., 1993b). The *Apachesaurus* is less than 1 m in length and is primarily found in fluvial floodplain and non-aquatic deposits and is associated with terrestrial animals.

In the study area, the bone fragments in the Moss Back submember may represent *Buettneria* because they are larger than expected for a small creature such as an *Apachesaurus*. In addition, the bones are in fluvial deposits (sandstone and gravel) as is expected with *Buettneria*.

Ichnofossils

Ichnofossils are relatively rare in the field area and occur only in the Monitor Butte, Bluewater Creek, Owl Rock, and Church Rock members. The ichnofossils are interpreted to represent roots and small, unidentified burrowing creatures.

Stratigraphy and Depositional Environments

Moenkopi Formation

The Lower to Middle Triassic Moenkopi Formation represents a complex of deposits formed in both continental and marine environments (Stewart et al., 1972b). Exposures near the study area probably represent fluvial deposits (Stewart et al., 1972b). The red color of the beds (Cooper et al., 1990) and the presence of evaporite deposits in the Moenkopi (Stewart et al., 1972b) are generally considered to reflect deposition in an arid environment (Stewart et al., 1972b; Blakey and Gubitosa, 1984).

Chinle Formation

Across most of the Colorado Plateau, the Upper Triassic Chinle Formation lies unconformably above the eroded Moenkopi Formation. This unconformity, referred to as the TR-3 unconformity (Hasiotis and Dubiel, 1993; Demko, 1995; Therrien et al., 1999; Hasiotis et al., 2001), represents a period of erosion during which rivers cut away the upper part of, or, in some places, the entire Moenkopi Formation.

Shinarump Member. Channels that had been cut into the Moenkopi were filled by the sandstone, conglomerate, and mudstone of the Shinarump Member. This uneven base resulted in differing thicknesses in and discontinuous occurrences of the Shinarump across the Colorado Plateau (Heckert and Lucas, 1996). Stewart et al. (1972a), for instance, did not find the Shinarump in either the Horse Canyon or the Silver Falls Creek areas of the Grand Staircase-Escalante National Monument.

Trough and planar cross-bedding in the medium- to coarse-grained sandstone of the Shinarump in the study area records sediment accumulation during migration of several types of bedforms in a fluvial environment. The bedforms formed under variable flow velocities that are recorded by the presence of both planar and trough cross-beds and that could have been the result of seasonal fluctuations in flow or channel migration. Both trough and planar cross-beds were formed when sedimentation rates were high (Miall, 1996).

The conglomerate in the Shinarump Member is clast supported, massive, and fills channels cut into the sandstone of that member reflecting local channeling events, perhaps the result of shifting river channels. The size of the clasts indicates a relatively high flow velocity (Miall, 1996).

In the Little Bown Bench area, the Mottled Strata submember is cut by a channel filled with the sandstone of the Shinarump submember. This channel, which is 1.5 m deep, widens upward from approximately 1 m at the base to 1.5 m at the top. The depth to height ratio of the channel and lack of disruption of the surrounding mudstone indicates that this channel is a "wadi" structure (Miall, 1996). Such structures, which have cutbank slopes in excess of 45°, are formed during rapid erosion in arid environments. Miall (1996) reported a similar channel in the Canyon de Chelly National Monument, Arizona, where the Shinarump submember fills a channel cut into the Canyon de Chelly Sandstone (Miall, 1996).

Exposures of the uppermost Shinarump Member contain lateral accretion surfaces (Fig. 14). These surfaces have average widths of 5 m. Based on Miall's (1996) calculation that accretion surfaces have an average width of two-thirds that of the channel in which they form, the channel width for these deposits is estimated at approximately 7.5 m.

Ripple laminations and fine-grained sediment increase in abundance upward in the Shinarump Member (Fig. 16), indicating a progression from higher energy flow to lower energy flow. As is the case in Shinarump exposures across the Colorado Plateau, these deposits preserve a record of transition from a channel-dominated to a floodplain-dominated depositional environment.

The source of Shinarump sediment has been interpreted to have been located to the south and east, probably in uplifted Paleozoic rocks and volcanic rocks that presently are not exposed in southwestern Arizona (Harris et al., 1997; Demko, 1995; Stewart et al., 1972a, 1986). This is consistent with the general westward flow direction, measured from cross-bedding (Fig. 31).

<u>Monitor Butte Member</u>. The Monitor Butte Member lies partially in a large paleovalley cut into the Shinarump Member (Demko et al., 1998; Dubiel et al., 1999). In the study area, the contact between the Shinarump Member and Monitor Butte Member is

conformable as recorded by similar lithofacies, including the poorly sorted lag deposits containing clasts of chert, siltstone, sandstone and petrified wood fragments, and by similar sedimentary structures such as the accretionary surfaces.

The two informal submembers of the Monitor Butte Member preserved in the study area record a series of local events. The lower informal submember consists of interbedded siltstone and sandstone deposited in lacustrine and fluvial settings, respectively. The upper informal submember consists of green siltstone and represents quiet lacustrine sedimentation, as indicated by the fine-grained sediment, the well preserved leaves, and the presence of symmetrical ripples.

The lacustrine deposits laterally grade into paleosols, which record the floodplain environment surrounding the lake(s). The development of Bsc and Btc horizons indicates that the floodplain was at least seasonally dry.

Bluewater Creek Member. In the study area, this member consists of three facies: a sandstone facies, a conglomerate facies called the Wolverine conglomerate, and a mudstone facies. Both the sandstone and Wolverine conglomerate facies of the Bluewater Creek Member fill channels cut into the Monitor Butte Member. For the sandstone facies, the best exposure of this relationship is in the Badger Butte area, where there is a 3-m-deep channel. In the center of the channel, current ripples are preserved. Near the channel margins, symmetrical ripple marks possibly represent ponds.

The best example of channeling for the conglomerate facies is in the Wolverine Bench area, where the conglomerate fills a channel cut through the older paleosols of the

Monitor Butte Member. The internally bedded limestone clasts in the conglomerate appear to be intrabasinal, freshwater limestones, probably of lacustrine origin, whereas the nodular calcite clasts appear to be nodules from underlying soils.

The mudstone facies of the Bluewater Creek is interpreted to represent paleosols. The mudstone probably was deposited by flood events on the fluvial floodplain at the same time as conglomerate was being deposited in the channel; later, as the river channel migrated, the river cut into the older mudstone, and the Bluewater Creek sandstone facies was deposited in these channels.

The Bluewater Creek is locally discontinuous, occurring in only four of the five measured sections (Appendix), and both channel facies are not always present. The Bluewater Creek Member is discontinuous across the Colorado Plateau (Heckert and Lucas, 1996).

Petrified Forest Member. The base of the Petrified Forest Member marks the beginning of the dominance of interchannel and floodplain deposits with minor fluvial sandstone and conglomerate layers. The bentonitic nature of the mudstones in the Petrified Forest Member indicates a strong volcanic sediment component. Volcanic debris is unstable in near-surface conditions and readily alters to bentonite (Schultz, 1963).

Lower Petrified Forest Submember. The mudstone in the Lower Petrified Forest submember is interpreted primarily as a floodplain deposit. The lateral extent, fine-grained nature, and development of paleosols in the mudstone suggest that these are floodplain deposits that were subaerially exposed for significant periods of time. This would have been the case if they were deposited during flood events.

Overbank events can only deposit sediment over large areas where the topography is very subdued. Rivers with large floodplains typically have fine-sediment loads that can be deposited as sheetlike units over many tens of square meters or even square kilometers (Miall, 1996). The mudstone that consistently dominates the Lower Petrified Forest submember throughout the field area supports the interpretation of the depositional agent as a river with a fine-grained sediment load, such as a meandering river, that deposited its sediment across a significant area.

Moss Back Submember. The basal conglomerate and generally fine-grained, cross-laminated brown sandstone of the lowermost Moss Back submember rest on a major unconformity. The conglomerate represents the initial channel fill. Small-scale features and fine grain size in the overlying brown sandstone indicate that it was deposited by low-velocity currents (Miall, 1996).

Above the brown sandstone and conglomerate is well sorted, cross-bedded, lavender and/or white sandstone that reflects a migrating channel. Multistory channel sequences and the presence of lateral accretion surfaces indicate that channel migration occurred repeatedly in this interval. The presence of conglomerate and trough cross-bedded medium- to coarse-grained sandstone indicates a moderate to high flow velocity (Miall, 1996).

The sedimentary structures of the Moss Back submember also suggest the way in which the permineralized trees in this submember were deposited. The fossilized trees occur within sets of cross-bedded sandstone (Fig. 41), indicating that the processes forming the cross-beds remained constant before, during, and after deposition of the trees. The presence of several centimeters of cross-bedded sandstone vertically between individual logs indicates that the logs were not deposited simultaneously. It is possible that the trees reflect regular stream processes such as undercutting. Trees may have fallen into the stream and were preserved when covered by stream sediment. The lack of branches and bark on the permineralized trees in the study area, however, suggest that the stream transported the logs before deposition. Trees were downed and covered at different times creating a petrified wood interval rather than a single layer representing a single event.

Mudstone exhibiting paleosol features is interbedded with the sandstones of the Moss Back submember throughout its exposure. This indicates that the stream that deposited the Moss Back was migrating back and forth across its floodplain. As the stream migrated, it covered old flood deposits with fluvial sandstones and left old fluvial sandstones to be covered with new flood fines.

The presence of paleosol features in the mudstone indicates that deposition of this submember took place over a considerable length of time and that the sediment was subaerially exposed long enough for soils to form. The soils present are immature, with platy peds, but still took some time to form (Retallack, 2001).

The erosional surface at the base of the Moss Back submember is the TR4 unconformity (Lucas, 1993, 1994; Heckert, 1995; Heckert and Lucas, 1996; Lucas et al., 1997a, b). The development of this unconformity is currently poorly understood, but it has been briefly addressed by a number of previous workers. Lucas (1991, 1997) stated that erosion was due to a global lowering of sea level; later, as the sea level began to rise, the Moss Back submember and Sonsela Sandstone were deposited. Blakey and Gubitosa (1984) believed that it was caused by fluctuations in subsidence rates, whereas Therrien et al. (1999) attributed it to frequent avulsion. The erosional event that caused this unconformity removed as much as 100 m from the underlying units, and in some places, such as at Rio Salado, New Mexico, it removed the entire the Lower Petrified Forest submember (Heckert and Lucas, 1996). The TR4 unconformity occurs at the Carnian-Norian boundary, and, according to Embry (1997), it represents a second-order sequence boundary formed by a drop in base level in response to a significant plate tectonic reorganization.

Upper Petrified Forest Submember. The sandstone and mudstone of the Upper Petrified Forest submember record an environment dominated by interchannel sedimentation where fine-grained sediment accumulated gradually through flood events and was reworked during pedogenesis. Isolated sandstone lenses in the Upper Petrified Forest submember likely record crevasse channeling events. Flow direction, measured on cross-bedding, is southeasterly, normal to the north to northwesterly flow typical of the

Chinle. Crevasse channels with an orientation roughly perpendicular to the main channel would deposit such sandstones.

The Zebra sandstone of this study is correlative with the Capitol Reef bed identified by Stewart (1972a). Stewart noted that the grayish-purple, light greenish-gray and grayish-red, medium-grained, moderately sorted, poorly-cemented sandstone of the Capitol Reef bed was recognized only in the Capitol Reef and northern Circle Cliffs areas. Due to its limited geographical extent, Stewart (1957, 1961) and Stewart et al. (1972a) are among the few workers to reference this unit in studies of the Chinle Formation.

Similarities between the Zebra sandstone and the Capitol Reef bed include significant lateral extent, significant thickness, and the presence of permineralized wood. In field reconnaissance of two of Stewart's sections, mudstone, coarse sand, and conglomerate lenses, similar to those seen in the study area, were found in addition to the brightly colored sandstone described by Stewart (1961) and Stewart et al. (1972a).

In addition to the similar physical attributes of the two units, the Zebra sandstone and the Capitol Reef bed are located in similar stratigraphic positions in the Upper Petrified Forest submember. Therefore, based on the similarity in appearance and stratigraphic occurrence between the two beds, the Zebra sandstone is correlated to the Capitol Reef bed.

The Zebra sandstone and correlative Capitol Reef bed were deposited on a channeled surface that indicates an erosional unconformity similar to that producing the Shinarump Member and Moss Back submember. The more limited geographical extent of the Zebra sandstone, however, suggests that the downcutting event occurred on a more limited scale.

Similar localized sandstone bodies occur at other locations on the Colorado Plateau in the Upper Petrified Forest submember. Lucas (1993, 1994), for instance, identified units called the Painted Desert sandstones, Flattops sandstones, and the Black Forest volcaniclastic bed in Petrified Forest National Park, Arizona. Localized sandstone bodies such as these indicate that channeling followed by infilling, perhaps the result of channel shifting, was a common event throughout deposition of the Upper Petrified Forest submember.

Owl Rock Member. In the study area, the Owl Rock Member is dominated by mudstones that are interpreted to be paleosols. The fine-grained nature of these rocks and the development of paleosols indicate that the Owl Rock could have been deposited in a floodplain environment similar to that in which the Petrified Forest Member was deposited. The lack of sandstone lenses in the Owl Rock suggests that channels were few and crevasse channeling events were no longer occurring in this area. In some areas outside the study area, the Owl Rock Member contains micritic limestones that probably were deposited in lacustrine environments, and siltstones and sandstones that were deposited on the lake margins (Dubiel, 1989b).

Church Rock Member. The Church Rock Member in the study area is dominated by red, clay-rich mudstones interpreted to be paleosols. Sandstone lenses are lacking in the lower part of the unit, but in the upper part of the unit there are very fine-grained sandstone lenses. The fine-grained nature of these rocks and the development of paleosols indicate that the Church Rock could also have been deposited in a floodplain environment. The lack of significant sandstone lenses in the lower part of the unit and the presence of only very fine-grained sandstone lenses in the upper part suggests that low paleoflow persisted from deposition of the Owl Rock to that of the Church Rock.

The Church Rock appears to conformably overlie the Owl Rock Formation, but the red mudstones of the Church Rock are dramatically different from those of the underlying Owl Rock Member in their bold coloration, lower degree of cementation, lower carbonate content, and structure. The differences between these two units probably record different depositional environments, but the difference has not been ascertained by this study. It is possible, although not apparent in the study area, that the two units are not conformable. The contact between the two units may have been obscured by soil forming processes.

Marzolf (1997) placed the end of the Triassic at the Owl Rock/Church Rock contact and placed an unconformity between the two members because the Church Rock overlies formations of different ages in different areas on the San Rafael Swell in Utah (Lucas, 1991). According to Lucas et al. (1997b), however, this unconformity marks the Norian-Rhaetian boundary in the Triassic and is referred to as the TR-5 unconformity.

Wingate Formation

The large-scale cross-beds in the Wingate are considered to be the result of eolian deposition (Lucas et al., 1997b). The onset of eolian deposition marked a dramatic change in the nature of the sediment deposited and the climatic conditions present at the time of its deposition. Some workers place the J-0 unconformity (the beginning of the Jurassic) at the base of the Wingate Formation (Lucas, 1991; Lucas et al., 1997b).

Petrography

All samples studied are litharenites (Fig. 37). The amount of quartz is variable, but amounts of undulatory quartz consistently exceed the amounts of nonundulatory quartz. There are limited amounts of feldspar in the samples, including trace amounts of microcline, which is present in all samples.

Lithic grains in the samples include those that are identifiable as volcanic and those with indeterminate identity. The indeterminate grains could include metamorphic rock fragments and/or sedimentary rock fragments such as chert. Those grains that are clearly identifiable as volcanic in origin contain microphenocrysts of plagioclase feldspar.

The Zebra sandstone contains slightly more quartz and fewer lithic clasts than the Moss Back submember (Fig. 37). A decrease in the amount of lithic material in the Zebra sandstone could be due to decreased availability or greater destruction of unstable lithic clasts during diagenesis.

Colorless mica, which probably is leached biotite rather than muscovite (Robert Rose, pers. comm., 2002), occurs in a majority of the samples and suggests a metamorphic or igneous source for some of the sediment (Boggs, 1992).

The cement of the sandstones sampled is mainly silica with varying amounts of carbonate. One possible source for the silica is volcanic ash. Glass shards could have devitrified to create the large number of microcystalline grains common in all of the samples (Robert Rose, pers. comm., 2002; Andrei Sarna-Wojcicki, pers. comm., 2002). The presence of ash in the study area is also indicated by the dominance of smectite clay and by the permineralization of trees, which required a rich silica source such as ash. Any original ash beds may have been destroyed by soil-forming processes and diagenesis so that they are no longer identifiable. Ash could have come from a chain of volcanoes along the west-coast of the continent (Fig. 5) and/or the south where the provenance for at least some of the Chinle sediment is located.

Where carbonate is present in the sandstones, it replaces, to varying degrees, adjoining grains (Fig. 39). Particularly impacted by this are the lithic grains; the percentage of lithics decreases as the percentage of carbonate increases (Fig. 50). The larger crystal surface areas within the polycrystalline grains probably made them more susceptible to alteration.

A plutonic and/or metamorphic source for part of the sandstone samples is indicated by the presence of microcline and mica. A volcanic source is indicated by microphenocryst-bearing volcanic rock fragments and by the silica-rich matrix. Some lithic clasts and biotite may suggest a metamorphic source. A sedimentary source is

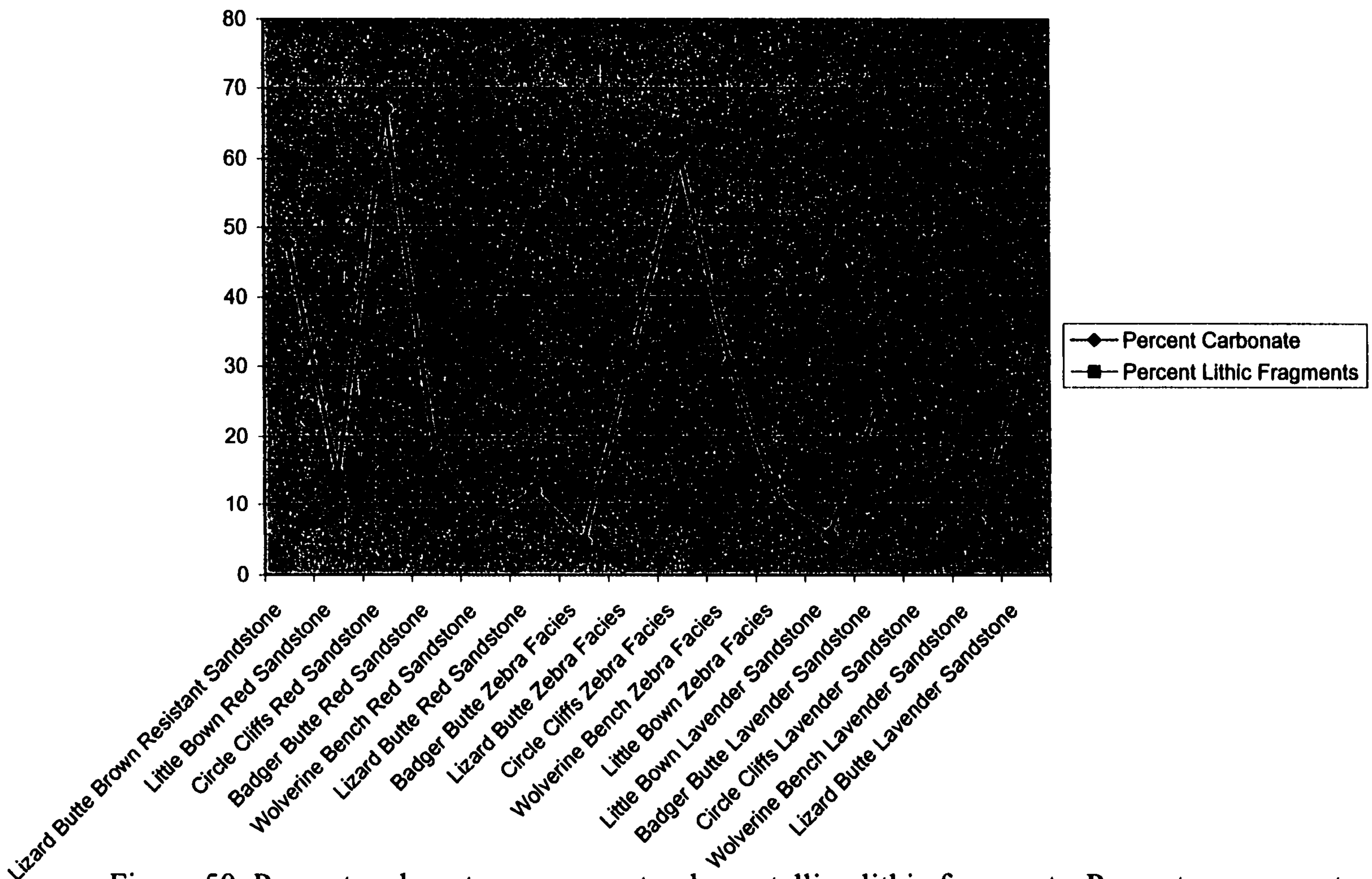


Figure 50. Percent carbonate vs. percent polycrystalline lithic fragments. Percentages are out of total counts of lithic, quartz, and feldspar clasts and carbonate in each sample.

indicated by the possible presence of sedimentary lithic clasts including chert. The indeterminate nature of most of the microcrystalline lithics, however, obscures the issue of provenance. Regional geography at the time of deposition can help narrow possible source areas.

Igneous and metamorphic sources lay to the south and east of the study area. The Mogollon Highlands to the south exposed a variety of Precambrian igneous and metamorphic rocks (Stewart et al., 1972a; Blakey and Gubitosa, 1983). The ancestral Rocky Mountains to the east were rich in Precambrian crystalline rocks (Stewart et al., 1972a; Blakey and Gubitosa, 1983). Possible volcanic sources are a chain of volcanoes to the west (Harris et al., 1997) and an unknown volcanic source to the south (Stewart et al., 1972a; Sigleo, 1978a,b).

Because the amount of volcanic material in the samples cannot be determined accurately, and because there are at least two source areas that contain plutonic and metamorphic rocks, determination of the influence that each area had on the composition of the sandstones is not possible with the data acquired in this study.

The sandstones looked at in this study are immature as indicated by the presence of unstable rock fragments. Also, grains in all samples are either angular or subangular, there is a low degree of sphericity, and there are high amounts of undulatory quartz. Sorting, however, is good, indicating a moderate amount of reworking.

Post-depositional compaction and alteration of the sandstones, indicated by distorted grains of mica and polycrystalline lithic clasts and by introduction of silica and carbonate material during diagenesis has resulted in low porosity in the Chinle samples.

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During Owl Rock and Church Rock member deposition, the climate shifted to one of increased aridity as indicated by the presence of Aridisols and Alfisols.

Previous workers had developed four different interpretations of the climate and climatic change during deposition of the Chinle. Blakey and Gubitosa (1984), for example, suggested a progression from an arid environment to an increasingly humid environment. Harris et al. (1997) suggested a humid environment dominated by swampy floodplains. Demko (1995), Dubiel (1989b, 1991), and Fiorillo et al. (2000) interpreted an environment dominated by floodplains with seasonal rainfall, while Hunt et al. (1993b) suggested a progression from a wet environment that supported fluvial and lacustrine features to a drier environment with shallow, isolated lakes. Data developed here from the study of the Wolverine Petrified wood area basically support the interpretations of Hunt et al. (1993b).

The changes in climatic conditions can by explained by consideration of the paleogeography during the Late Triassic. Paleomagnetic data indicate that the Chinle was deposited in an area that lay between 5° and 15° north of the equator (Bazard and Butler, 1991; Hasiotis and Dubiel, 1993; Kent and Witte, 1993). Because of the distribution of continental land mass and their proximity to the equator, during the Triassic, the Chinle depositional basin lay in an area of intense monsoonal precipitation (Hasiotis and Dubiel, 1993; Wilson et al., 1994; Chan, 1999). Near the end of Chinle deposition, near the end of the Triassic, the rotation of (Bazard and Butler, 1991; Kent and Witte, 1993) and the beginning of the breakup of Pangea resulted in shifting climatic patterns (Wilson et al., 1994; Chan, 1999), and the Chinle depositional basin became increasingly arid. The switch to arid conditions is also shown by the switch to eolian deposition at the beginning of the Jurassic (Dubiel and Hasiotis, 1994; Demko, 1995).

COMPARABLE MODERN SEDIMENTARY SETTINGS

The mechanism capable of depositing the laterally continuous members of the Chinle Formation is poorly understood. Gaining an understanding of how these sediment types can be deposited over an exceedingly broad area is important in understanding the depositional environment of the Chinle Formation. One way to better understand how the sediment of the Chinle was deposited is to compare the Chinle depositional basin with a comparable modern depositional basin.

Important characteristics of the Chinle Formation that should be considered when searching for a modern analog include (1) the climate, (2) the sediment sources and type, and (3) the geographic extent of the basin in which is was deposited. The Chinle was deposited in a climate with seasonal, perhaps monsoonal (Demko, 1995; Dubiel, 1989b), precipitation. Sediment was derived from at least two different sources, and it was deposited over a vast area.

The Indo-Gangetic or Bihar plains are one of the world's largest areas of Quaternary alluvial sedimentation. They extend from the foothills of the Himalaya southward for about 200 km to the hills of Peninsular India and run 3000 km east-west along the Himalayan front (Sinha and Friend, 1994). The Bihar plains experience a monsoonal climate with intense seasonal precipitation. Large amounts of mud, some sand, and limited amounts of conglomerate are transported to the plains from the foothills to the south and the Himalaya to the north (Sinha and Friend, 1994). Because of these similarities, the northern Bihar plains of India may be one of the best modern analogs to the depositional basin of the Chinle Formation.

On the Bihar plains, water is carried off the front of the foothills to the south and the Himalayas to the north by a system of small rivers. When there is rainfall, the majority of the rain drains off quickly without infiltrating the soil, and this leads to flash floods. These flood events result in the accumulation of thick muddy overbank deposits. The river channels themselves are recorded by isolated discontinuous sandy beds, which occur randomly throughout the thick deposits of overbank mud because of flood related avulsion (Sinha and Friend, 1994). The sedimentary record left by this type of depositional environment is summarized in Figure 51. Sinha and Friend (1994) recognized that there were several possible geometries that the sedimentary record could take depending on the location of the deposition (Fig. 51). In both the foothills-fed and plains-fed models the key features are the thick deposits of mudstone and the isolated sandstone lenses.

Because of the similar climate, sediment sources, and the geographic extent of the basin in which it was deposited, the sedimentary record of the northern Bihar plains should be a good analog of the sedimentary record preserved in the Chinle Formation. Either the foothills-fed or the plains-fed model could pertain to the Chinle exposed in the study area (Fig. 51). The thick mudstone deposits in the study area were likely deposited by processes similar to those that laid down the thick mudstone deposits on the Bihar Plains. The minor amounts and channel-form geometry of sandstone bodies in the mudstones also are similar. The Shinarump and Moss Back sandstones of the Chinle,

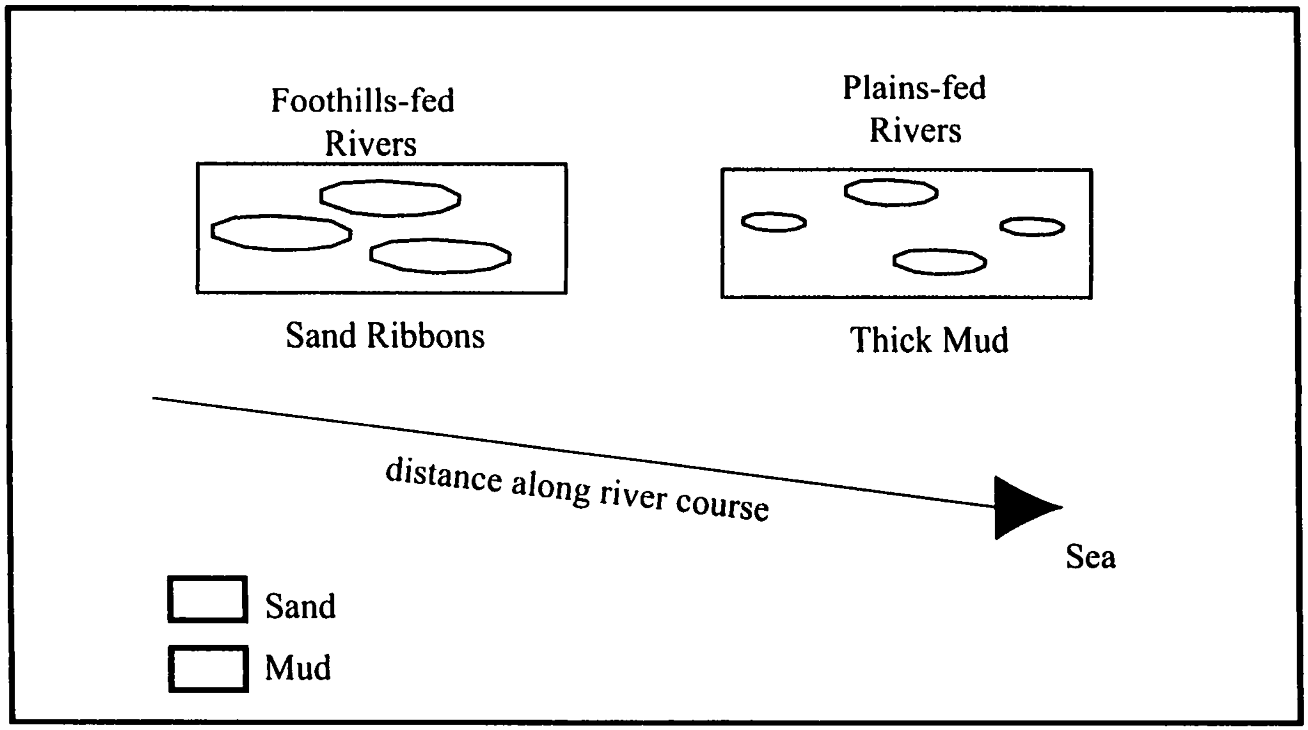

Figure 51. Subsurface geometry of sandstone bodies deposited in the northern Bihar plains of India (adapted from Sinha and Friend, 1994).

however, are regionally extensive, indicating that they formed under different depositional conditions than those currently seen in the Bihar plains of India.

MAJOR EROSIONAL EPISODES

One mechanism for the creation of laterally extensive sheets of sandstone, which are present in the Chinle Formation, is the periodic interruption of sedimentation by widespread erosional events. The sandstones themselves represent sediment that accumulated during and following erosional events inferred to have been caused by regional and global falls in base level and define three depositional sequences.

Sedimentary sequences record the stages of relative sea level fall, lowstand, and transgression in very specific ways (Embry and Myers, 1996). During development of the lowstand systems tract, channels initially are confined to their beds resulting in reworking of channel deposits. Over time, however, the channels migrate, resulting in the reworking of floodplain deposits and removal of fines. This results in laterally extensive deposits composed of medium- to coarse-grained, moderately well sorted, rounded, and sized sediment. In the geologic record this is preserved as an extensive fluvial sandstone unit composed of multi-story, multi-lateral sandstone bodies.

As the relative sea level rises, the increase in accommodation space and overall reduction in stream gradient results in the development of vast floodplains with a few stream channels (Embry and Myers, 1996). This is recorded by laterally extensive, thick deposits of floodplain fines such as mudstone with a few sandstone channels.

The lowest major unconformity in the study area occurs at the base of the Chinle Formation, at the base of the Shinarump Member, which fills valleys incised into the Lower and Middle Triassic Moenkopi Formation. This unconformity is the TR-3 unconformity, which occurs across the Colorado Plateau (Therrien et al., 1999). This erosional episode was followed by deposition of the first depositional sequence: the Shinarump to the base of the Moss Back. This sequence includes lacustrine, channel, and interchannel deposits.

The second major unconformity occurs in the Petrified Forest Member at the base of the Moss Back submember, which filled channels cut into the Lower Petrified Forest submember during development of the TR-4 unconformity. This unconformity marks the beginning of the next depositional sequence, which consists of the Moss Back and Upper Petrified Forest submembers to the base of the Zebra sandstone. The TR-4 unconformity occurs throughout the Colorado Plateau and represents up to 100 m of relief cut into the Lower Petrified Forest submember (Heckert and Lucas, 1996). The work of Embry (1997) indicates that a global sea level drop was responsible for the TR-4 unconformity.

The amount of section eroded from the Lower Petrified Forest submember in the study area is unknown, but the channels at the base of the Moss Back submember show that an erosional unconformity does exist. During eustatic lowstand, rivers reworked channel and floodplain deposits as they meandered across the Colorado Plateau, gradually removing the fines. The multi-story, multi-lateral sandstone bodies that resulted are now called the Moss Back submember (= Sonsela Sandstone) of the Petrified Forest Member. As sea level rose and accommodation space increased, widespread floodplain deposits of mudstone with sandstone channels accumulated.

This scenario is similar to that suggested by Blakey and Gubitosa (1983), although Blakey and Gubitosa (1983) pointed to changing subsidence rates rather than base level fluctuations as the mechanism behind deposition of the Sonsela Sandstone. The effect of each of these mechanisms is similar because in both cases the amount of accommodation space is similarly changed.

The third major unconformity occurs in the Upper Petrified Forest submember at the base of the Zebra sandstone. This sandstone fills channels cut into the underlying mudstone of the Upper Petrified Forest Member and marks the beginning of the third depositional sequence, the Zebra sandstone through the Owl Rock Member. The base of the Zebra sandstone, although clearly resting in channels, is relatively flat throughout the study area. Because of this and the relatively local extent of this unconformity, which has led to this unconformity being less well studied than the TR-3 and TR-4 unconformities, the amount of sediment removed by the event that caused this unconformity has yet to be determined.

A fourth possible unconformity is at the base of the Church Rock, and, in the study area, is only indicated by a great difference in paleosol type between the Church Rock and the underlying Owl Rock. Although no unconformity was recognized in the Wolverine Petrified Wood Area, it has been recognized by workers across the Colorado Plateau. This unconformity, identified as the TR-5 unconformity, marks the base of the last Triassic sequence (Lucas et al., 1997b). The TR-5 unconformity likely represents a base level change that was global in scale, as indicated by its extent across the Colorado Plateau. The base of the Wingate Sandstone marks the J-0 unconformity and the beginning of the Jurassic (Demko, 1995; Dubiel and Hasiotis, 1994).

Two additional significant erosional events recorded in the study area appear to be of local extent. The first event is recorded at the base of the Wolverine conglomerate in the Bluewater Creek Member. This conglomerate fills a laterally restricted, shallow channel that is cut into both the interbedded sandstone and siltstone informal submember and the mudstone facies of the Monitor Butte Member. The second event is recorded at the base of the sandstone facies of the Bluewater Creek Member. This facies overlies the Wolverine conglomerate and fills a channel cut into the mudstone facies of the Bluewater Creek Member. In some areas, this facies has been totally removed and the sandstone facies fills channels cut directly into the interbedded sandstone and siltstone submember and the mudstone facies of the underlying Monitor Butte Member. These minor erosional episodes, which are only recorded in the study area, probably represent more local erosional events such as shifting of a major river channel.

CONCLUSIONS

The sedimentary facies, structures, and fossils in the Wolverine Petrified Wood Area suggest that all units of the Chinle, except for the lacustrine facies of the Monitor Butte Member, were deposited by fluvial processes. The presence of paleosol features in the mudstones, which dominate the Chinle in the study area, shows that many of the flood deposits from the fluvial systems were altered by pedogenic processes. The presence of Vertisols in the Monitor Butte, Bluewater Creek, and Petrified Forest members indicate that the climate during deposition of the majority of the Chinle Formation was seasonal; the presence of Aridisols in the Owl Rock Member indicates increasing aridity near the end of Chinle deposition.

Interbedded with the mudstones of the Chinle are several sandstone bodies including the Shinarump Member, Moss Back submember of the Petrified Forest Member, and Zebra sandstone of the Upper Petrified Forest submember. Petrographic observations and a small number of paleocurrent measurements in these sandstones suggest that the sediment was derived primarily from the south with possible contributions from highlands to the east and from a volcanic arc to the west.

Contained within the sandstones are the fossil trees for which the Wolverine Petrified Wood Area was established. Permineralization of fossil wood indicates elevated groundwater levels and silica enrichment of slightly basic groundwater for a significant period of time after deposition. Bones found in the sandstone of the Moss Back submember are too few to make any meaningful interpretation but may be from

Buettneria, which required a fluvial or lacustrine habitat and is commonly found in fluvial channel deposits. Additional fossils, including carbonized logs and carbonized leaves in the Shinarump, Monitor Butte, and Bluewater Creek members, indicate lacustrine and fluvial deposition, which is consistent with associated sedimentary facies and structures. The identification of the leaves in the Monitor Butte and Bluewater Creek members as *Zamites powelli* supports a seasonal, warm climate during the time of their deposition.

The major sandstone beds represent a series of downcutting events that resulted in extensive erosion of older units and deposition of multi-story, laterally extensive sand bodies. Three, possibly four, main sequence boundaries, at the bases of the Shinarump Member, Moss Back submember, Zebra sandstone, and Church Rock Member, and two local erosional boundaries, at the base of the Wolverine conglomerate and the base of the sandstone facies of the Monitor Butte Member, were identified. The main sequence boundaries were probably caused by global lowering of sea level while the local surfaces were likely the result of more regional events.

REFERENCES CITED

Allen, V.T., 1930, Triassic bentonite in the Painted Desert: American Journal of Science, v. 14, p. 283-288.

Ash, S.R., 1974, Guidebook to Devonian, Permian, and Triassic plant localities, east-central Arizona: Paleobotanical Section of the Botanical Society of America 25th Annual AIBS Meeting, p. 40-50.

Ash, S.R., 1975, *Zamites powelli* and its distribution in the Upper Triassic of North America: Paleontographica, v. 149B, p. 139-152.

Ash, S.R., 1976, Preliminary report on the floral zones in the Upper Triassic Chinle Formation, southwestern United States [abs.]: Geological Society of America Abstracts with Programs, Rocky Mountain Section, v. 8, p. 562.

Ash, S.R., ed., 1978, Geology, paleontology, and paleoecology of a Late Triassic lake, western New Mexico: Provo, Utah, Brigham Young University Geology Studies, v. 25, 100 p.

Bazard, D.R., and Butler, R.F., 1991, Paleomagnetism of the Chinle and Kayenta Formations, New Mexico and Arizona: Journal of Geophysical Research, v. 96, p. 9847-9871.

Blakey, R.C., and Gubitosa, R., 1983, Late Triassic paleogeography and depositional history of the Chinle Formation, southern Utah and northern Arizona, *in* Reynolds, M.W., and Dolly, E.D., eds., Mesozoic paleogeography of west-central United States: Denver, Rocky Mountain Section S.E.P.M., p. 57-76.

Blakey, R.C., and Gubitosa, R., 1984, Controls of sandstone body geometry and architecture in the Chinle Formation (Upper Triassic), Colorado Plateau: Sedimentary Geology, v. 38, p. 51-86.

Blodgett, R.H., 1988, Calcareous paleosols in the Triassic Dolores Formation, southwestern Colorado, *in* Reinhardt, J. and Sigleo, W.R., eds., Paleosols and weathering through geologic time: Geological Society of America Special Paper 216, p.103-121.

Boggs, S., Jr., 1992, Petrology of sedimentary rocks: New York, Macmillan Publishing Company, 707 p.

Buurman, P., 1972, Mineralization of fossil wood: Scripta Geologica, v.12, p. 1-43.

Chan, M.A., 1999, Triassic loessite of north-central Utah: stratigraphy, petrophysical character, and paleoclimate implications: Journal of Sedimentary Research, v. 69, p. 477-485.

Chronic, H., 1986, Roadside geology of Arizona: Missoula, Montana, Mountain Press Publishing Company, 314 p.

Compton, R.R., 1985, Geology in the field: New York, John Wiley and Sons, 398 p.

Cooper, J.D., Miller, R.H., and Patterson, J., 1990, A trip through time: principles of historical geology: Columbus, Ohio, Merrill Publishing Company, 544 p.

Curray, J.R., 1956, The analysis of two dimensional orientation data: Journal of Geology, v. 64, p. 117-131.

Daugherty, L.H., 1941, The Upper Triassic flora of Arizona: Washington, D.C., Carnegie Institution of Washington, 108 p.

Demko, T.M, 1995, Taphonomy of fossil plants in the Upper Triassic Chinle Formation (Petrified Forest National Park, Arizona) [PhD thesis]: Tucson,University of Arizona, 274 p.

Demko, T.M., Dubiel, R.F., and Parrish, J.T., 1998, Plant taphonomy in incised valleys: implications for interpreting paleoclimate from fossil plants: Geology, v. 26, p. 1119-1122.

Dickinson, W.R., 1970, Interpreting detrital modes of greywacke and arkose: Journal of Sedimentary Petrology, v. 40, p. 695-707.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2164-2182.

Dubiel, R.F., 1989a, Sedimentological and revised nomenclature for the upper part of the Upper Triassic Chinle Formation and the Lower Jurassic Wingate Sandstone, northwestern New Mexico and northeastern Arizona, *in* Anderson, O.J., Lucas, S.G., Love, D.W., and Cather, S.M., eds., Southeastern Colorado Plateau: New Mexico Geological Society, 40th Field Conference Guidebook, p. 213-223.

Dubiel, R.F., 1989b, Depositional environments of the Upper Triassic Chinle Formation in the eastern San Juan Basin and vicinity, New Mexico: U.S. Geological Survey Bulletin 1808, 22 p.

Dubiel, R.F., 1991, Sedimentology and depositional history of the Upper Triassic Chinle Formation in the Uinta, Piceance, and Eagle basins, northwestern Colorado and northeastern Utah: U.S. Geological Survey Bulletin 1787-W, 25 p.

Dubiel, R.F., and Hasiotis, S.T., 1994, Integration of sedimentology, paleosols, and trace fossils for paleohydrologic and paleoclimatic interpretation in a Triassic tropical alluvial system (abs.): Geological Society of America Abstracts with Programs, v. 26, p. A-502.

Dubiel, R.F., Hasiotis, S.T., and Demko, T.M., 1999, Incised valley fills in the lower part of the Chinle Formation, Petrified Forest National Park, Arizona: complete measured sections and regional stratigraphic implications of Upper Triassic rocks, *in* Santucci, V. and McClelland, L., eds, National Park Service Paleontological Research, v. 4, p. 78-84.

Dubiel, R.F., Parrish, J.T., Parrish, J.M., and Good, S.G., 1991, The Pangean monsoon-evidence from the Upper Triassic Chinle Formation, Colorado Plateau: Palaios, v. 6, p. 347-370.

Easterbrook, D.J., 1993, Surface processes and landforms, Upper Saddle River: New Jersey, Prentice Hall, 520 p.

Embry, A.F., 1997, Global sequence boundaries of the Triassic and their identification in the Western Canada Sedimentary Basin: Bulletin of Canadian Petroleum Geology, v. 45, p.415-433.

Embry, A.F., and Myers, K.J., ed., 1996, Sequence stratigraphy: London, Blackwell Science, Ltd., 297 p.

Fiorillo, A.R., Padian, K., and Musikasinthorn, C., 2000, Taphonomy and depositional setting of the Placerias Quarry (Chinle Formation: Late Triassic, Arizona): Palaios, v. 15, p. 373-386.

Folk, R.L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's, 170 p.

Gray, J.J., Geitgey, R.P., and Baxter, G.L., 1989, Bentonite in Oregon: occurrences, analysis, and economic potential: State of Oregon Department of Geology and Mineral Resources Special Paper 20, 28 p.

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

Gregory, H., 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geological Survey Professional Paper 220, 200 p.

Gregory, H. E., and Williams, N.C., 1947, Zion National Monument, Utah: U.S. Geological Survey Bulletin, v. 58, p. 211-244.

Grim, R.E., and Guven, N., 1978, Bentonites: New York, Elsevier Scientific Publishing Company, 259 p.

Harris, A., Tuttle, E., and Tuttle, S.D., 1997, Geology of national parks: Dubuque, Iowa, Kendall/Hunt Pub. Co., 723 p.

Hasiotis, S.T. and Dubiel, R.F., 1993, Continental trace fossils, Petrified Forest National Park: tools for paleohydrologic and paleoecosystem reconstructions, *in* Santucci, V. L., ed., National Park Service Paleontological Research, v. 2, p. 139-148.

Hasiotis, S.T., Dubiel, R.F., and Demko, T.M., 1998, A holistic approach to reconstructing Triassic paleoecosystems: using ichnofossils and paleosols as a basic framework, *in* Santucci, V.L. and McClelland, L., eds, National Park Service Paleontological Research, v. 3, p. 122-124.

Hasiotis, S.T., Demko, T.M., and Dubiel, R.F., 2001, Shinarump incised valley cut and fill deposits, paleosols, and ichnofossils in the lower part of the Upper Triassic Chinle Formation, Petrified Forest National Park, Arizona: it really does exist, and it has regional stratigraphic implications(abs.): Geological Society of America Abstracts with Programs, v. 32, p. 11.

Heckert, A.B., 1995, Outcrop expression and significance for the TR-4 unconformity in west-central New Mexico: New Mexico Geology, v. 17, p. 29.

Heckert, A.B., and Lucas, S.G., 1996, Stratigraphic description of the TR-4 unconformity in west-central New Mexico and eastern Arizona: New Mexico Geology, v. 18, p. 61-70.

Herrick, A.S., Fastovsky, D.E., and Hoke, G.D., 1999, Occurrences of *Zamites powelli* in oldest Norian strata in Petrified Forest National Park, Arizona, *in* Santucci, V. and McClelland, L., eds., National Park Service Paleontological Research, v. 4, p. 91-95.

Holcombe, R.J., 2000, GEOrient: Department of Earth Sciences, The University of Queensland.

Hunt, A.P., Santucci, V.L., and Newall, A.J., 1993a, Late Triassic vertebrate taphonomy at Petrified Forest National Park, *in* Santucci, V.L., ed., National Park Service Paleontological Research, v. 2, p. 163-170.

Hunt, A.P., Santucci, V.L., and Wall, W.P, 1993b, Paleoecology of Late Triassic Metoposaurid amphibians: Evidence from Petrified Forest National Park: Park Science, p.12.

Kent, D.V., and Witte, W.K., 1993, Slow apparent polar wander for North America in the Late Triassic and large Colorado Plateau rotation: Tectonics, v. 12, p. 291-300.

Kiersch, G.A., 1955, Nonmetallic minerals–geology, evaluation, and uses: Mineral Resources Navajo–Hopi Indian Reservations, Arizona-Utah, v. 2: Tucson, University of Arizona Press, 105 p.

Kiersch, G.A., 1956, Metalliferous minerals and mineral fuels, geology, evaluation, and uses with a section on general geology: Mineral Resources Navajo–Hopi Indian Reservations, Arizona-Utah, v. 1: Tucson, University of Arizona Press, 75 p.

Kraus, K.J., and Middleton, L.T., 1987, Dissected paleotopography and base-level changes in a Triassic fluvial sequence: Geology, v. 15, p. 18-21.

Lucas, S.G., 1991, Revised Upper Triassic stratigraphy in the San Rafael Swell, Utah, *in* Chidsey, T.C., ed., Geology of east-central Utah: Utah Geological Association Publication 19, p. 1-8.

Lucas, S.G., 1993, Revised Upper Triassic stratigraphy in the Petrified Forest National Park, *in* Santucci, V.L., ed, National Park Service Paleontological Research, v. 2, p. 171-176.

Lucas, S.G., 1994, Revised Upper Triassic stratigraphy in the Petrified Forest National Park, northeastern Arizona (abs.): Geological Society of America Abstracts with Programs, v. 26, p. 27.

Lucas, S.G., 1997, Upper Triassic Chinle Group, western United States: a nonmarine standard for late Triassic time, *in* Dickens, J.M., ed., Late Paleozoic and early Mesozoic circum-Pacific events and their global correlation: Cambridge, Cambridge University Press, p. 209-228.

Lucas, S.G., and Hayden, S.N., 1989, Triassic stratigraphy of west-central New Mexico, *in* Anderson, O.J., Lucas, S.G., Love, D.W., and Cather, S.M., eds., Southeastern Colorado Plateau: New Mexico Geological Society Guidebook 40, p. 191-211.

Lucas, S.G., Heckert, A.B., and Anderson, O.J., 1997a, Triassic stratigraphy and paleontology on the Fort Wingate quadrangle, west-central New Mexico: New Mexico Geology, v. 19, p. 33-42.

Lucas, S.G., Heckert, A.B., Estep, J.W., Anderson, O.J., 1997b, Stratigraphy of the upper Chinle Group, four corners region, *in* Anderson, O.J., Kues, B., and Lucas, S.G eds., Mesozoic geology and paleontology of the four corners region: New Mexico Geological Society Guidebook, 48th Field Conference, p. 81-108.

Marcou, J., 1855, Resumé of a geological reconnaissance extending from Napolean, at the junction of the Arkansas with the Mississippi, to the Pueblo de Los Angeles in California, *in* Whipple, A.W., Report of exploration for a railway route near the thirty-fifth parallel of latitude from the Mississippi to the Pacific Ocean: United States Pacific Railroad Exploration Railway Route Mississippi to Pacific, v. 3, pt. 4, p. 165-171; also US Congress, 33rd, 1st session, House Ex. Document, v. 18, pt. 2.

Marzolf, J.E., 1997, The Triassic –Jurassic transition on the Colorado Plateau: regional considerations (abs.): Geological Society of America Abstracts with Programs, v. 21, p. 163.

Maxey, G.B., 1946, Geology of part of the Parant Range, Millard County, Utah: American Journal of Science, v. 29, p. 38.

Miall, A.D., 1996, The geology of fluvial deposits: New York, Springer-Verlag, 582 p.

Newberry, J.S., 1861, Geological report, *in* Ives, J.C., ed., Report upon the Colorado River of the west, explored in 1857 and 1858 by Lt. Joseph C. Ives: U.S. Engineer Department Geological Report, pt. 3, 154 p.

Pettijohn, F.J., Potter, P.E., and Siever, R., 1987, Sand and sandstone: New York, Springer-Verlag, 553 p.

Powell, J.W., 1876, Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto: New York, Julius Bien Lithography, 218 p.

Retallack, G.J., 1990, Soils of the past: an introduction to paleopedology: Boston, Unwin Hyman, 520 p.

Retallack, G.J., 2001, Soils of the past: an introduction to paleopedology: Boston, Blackwell Science, Inc., 404 p.

Robertson, J.F, 1981, Details of Chinle stratigraphy in northwest New Mexico: U.S. Geological Survey Professional Paper 1375, p. 56.

Schultz, L.G., 1963, Clay minerals in Triassic rocks of the Colorado Plateau: U.S. Geological Survey Bulletin 1147-C, 71 p.

Sigleo, A.C., 1978a, Geochemistry of silicified wood and associated sediments, Petrified Forest National Park, Arizona: Chemical Geology, v. 26, p 151-163.

Sigleo, A.C., 1978b, Organic geochemistry of silicified wood, Petrified Forest National Park, Arizona: Journal of the Geochemical Society and the Meteoritical Society, v. 42, p. 1397-1405.

Sinha, R., and Friend, P.F., 1994, River systems and their sediment flux, Indo-Gangetic plains, Northern Bihar, India: Sedimentology, v. 41, p. 825-845.

Stewart, J.H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: American Association Petroleum Geologists Bulletin, v. 41, p. 441-465.

Stewart, J. H., 1961, Stratigraphy and origin of the Chinle Formation (Upper Triassic) on the Colorado Plateau [PhD thesis]: Stanford, Stanford University, 184 p.

Stewart, J.H., Anderson, T.H., Haxel, G.B., Silver, L.T., and Wright, J.E., 1986, Late Triassic paleogeography of the southern Cordillera: The problem of a source for voluminous volcanic detritus in the Chinle Formation of the Colorado Plateau region: Geology, v. 14, p. 567-570.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972a, Stratigraphy and origin of the Chinle Formation and related Upper Triassic strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 690, 336 p.

Stewart, J.H., Poole, F.G., and Wilson, R.F., 1972b, Stratigraphy and origin of the Moenkopi Formation and related strata in the Colorado Plateau region: U.S. Geological Survey Professional Paper 691, 195 p.

Therrien, F., and Fastovsky, D.E., 2000, Paleoenvironments of early theropods, Chinle Formation (Late Triassic), Petrified Forest National Park, Utah: Palaios, v. 15, p. 194-211.

Therrien, F., Jones, M.M., Fastovsky, D.E., Herrick, A.S., and Hoke, G.D., 1999, The oldest Triassic strata exposed in Petrified Forest National Park revisited, *in* Santucci, V., and McClelland, L., eds, National Park Service Paleontological Research, v. 4, p. 101-108.

Tidwell, W.D., 1998, Common fossil plants of North America: Washington, Smithsonian Institution Press, 299 p.

Troeh, F.R., and Thompson, L.M., 1993, Soils and soil fertility: Oxford, Oxford University Press, 462 p.

Wilson, K.M., Pollard, D., Hay, W.W., Thompson, S.L., Wold, C.N., 1994, General circulation simulations of Triassic climates: preliminary results, *in* Klein, G.D., ed., Pangea: paleoclimate, tectonics, and sedimentation during accretion, zenith, and breakup of a supercontinent: Geological Society of America Special Paper 288, p. 91-116.

Witkind, I.J., and Thaden, R.E., 1963, Geology and uranium-vanadium deposits of the Monument Valley area Apache and Navajo counties, Arizona: U. S. Geological Survey Bulletin 1103, 154 p.

Zuber, J. D. and Parnell, R.A., 1989, A new paleoclimatic indicator from Triassic paleosols, Chinle Formation, Petrified Forest National Park, Arizona (abs.): Geological Society of America Abstracts with Programs, v. 21, p. 163.

APPENDIX

Description of Stratigraphic Columns

Wolverine Bench Stratigraphic Column

Measured about 1.4 km northwest of the Wolverine Petrified Wood area trailhead, 0.45 km north of the Wolverine Petrified Wood area boundary, on the eastern side of Wolverine Bench from approximately 37° 48'46" N, 111° 11'00"W to 37° 48'55"N, 111° 13'40"W.

Thickness in m

Wingate Formation

1. Sandstone, yellow on weathered and fresh surfaces, well sorted, medium-grained, quartz-rich, large-scale cross-beds, contact with underlying member is sharp, but does not appear erosional, resistant, cliff-former.

Top of section, top of formation.

Chinle Formation

Church Rock Member

2. Sandstone, dark red on weathered and fresh surfaces, fine-grained, generally massive with limited convolute bedding; elongate, horizontal, greenish-white lenses and stringers, some matrix-supported and composed of angular, poorly sorted white

clasts ranging from sand to cobbles 7 cm in diameter; matrix composed of red sandstone; unit less resistant than overlying Wingate, but still cliff-forming; protected by Wingate. *0.4*

1. Mudstone, brownish red and green mottled on weathered surfaces, light red and green mottled on fresh surfaces; green mottles round and regularly shaped in the lower exposures of the unit, root-like and layer-forming near the top of the unit; green layers average 5 cm thick; clay nodules average 1x2 cm, occur randomly throughout unit or in layers, in lower part nodules are stacked and increase in size upward until assuming columnar shapes defined by root traces; upper part composed of almost 100% smaller nodules; contact with the underlying unit gradational, interpreted to be a Btc soil horizon. *3.7*

Total of Church Rock Member *4.1*

Owl Rock Member

16. Cliff. *4.0*

15. Dolomite, hematite stained on weathered surfaces, grayish green on fresh surfaces; wavy beds, average 0.7 cm thick. *1.5*

14. Mudstone, red with green root-shaped mottles, concentration of green mottles increases upward; resistant cliff-former; angular blocks grade downward to wavy laminations; base of unit obscured by slope; interpreted to grade from a Bt soil horizon with angular blocky peds to a C soil horizon with horizontal structures. *2.4*

13. Dolomite, hematite stained on weathered surfaces, grayish green on fresh surfaces; cliff forming, beds 1 –2 cm thick, wavy, discontinuous, appears to weather to mudstone on top; fossil imprints present on surfaces of some beds; interpreted to be a K soil horizon, totally impregnated by carbonate. *1.0*

12. Cliff, 1.0-m-thick, red and green layered bed 3.5 m above the base. *7.6*

11. Mudstone, white to light green with light red mottles and light red with white to light green mottles on weathered surfaces; amount of green increases upward, red mottles have reduction spots and are irregularly shaped, green mottles are spherical; mottles 1-8 cm in diameter; well cemented with angular-blocky structure, blocks average 1 cm across, rounded on weathered edges; clay nodules common, oblong, average 2 x 1.5 cm;

interpreted to be a Btc soil horizon with angular to subangular blocky peds and nodules. *1.0*

10. Cliff. *1.5*

9. Mudstone, white to light green with light red mottles and light red with white to light green mottles on weathered surfaces; amount of green increases upward to solid green layer, red mottles have reduction spots and are irregularly shaped, green mottles are spherical, 1-8 cm in diameter; well cemented, angular-blocky structures, 0.5cm to 0.15m diameter, increasing downward, larger than in higher units, rounded on weathered edges; interpreted to be a Bt soil horizon because of the angular to subangular blocky peds, though the decreasing ped size may indicate a transition to an A horizon. *2.0*

8. Cliff. *2.2*

7. Mudstone, hematite stained on weathered surfaces, white to light green fresh surfaces; well cemented with angular-blocky structures averaging 1 cm in diameter; reacts slightly to dilute HCl;

interpreted to be a Btk soil horizon because of the angular blocky peds and the slight reaction to acid. *0.4*

6. Cliff. *4.2*

5. Mudstone, lower 0.65 m red with green mottles on weathered and fresh surfaces, mottles round, 1-3 cm in diameter; size of structures increases downward; 0.65 m from top of unit is a white to light green layer with red mottles on both weathered and fresh surfaces, red mottles irregularly shaped and 1-8 cm in diameter; below this, alternating red and green beds repeat twice more with well cemented, angular-blocky, 0.5-cm- to 5-cm-diameter structures; interpreted to be a Bt soil horizon with angular blocky peds, though the decreasing ped size may indicate a transition to an A soil horizon. *1.3*

4. Cliff. *2.0*

3. Mudstone, hematite stained on weathered surfaces, white to light green on fresh surfaces; well cemented, cliff-former; slight reaction to dilute HCl; layered appearance, 1-cm-thick ribbon-like layers combine into beds up to 8 cm thick throughout the unit; some

symmetrical ripples; interpreted to be a Ck soil horizon because of the preservation of relict bedding, structure, and slight reaction to dilute HCl. *0.6*

2. Mostly covered with 0.25-m-thick, red and green layered mudstone bed 2.5 m above base. *4.1*

1. Mudstone, white to light green and light red mottled on weathered surfaces; well cemented; breaks into 0.5-cm- to 3-cm-diameter angular-blocky structures; 1-3-cm-diameter chert nodules increase in abundance upward, appear concentrically formed, oblong or joined to form peanut shapes, no carbonate present; large (0.2-m-long), cylindrical, root traces or burrows, dark green or red, appear filled with silty material, interpreted to be a Btq soil horizon with angular blocky peds and accumulation of silica, or an E horizon due to its bleached appearance. *1.8*

Total of Owl Rock Member *37.6*

Petrified Forest Member

15. Mudstone, light lavender on weathered surfaces, brown with moss-green mottles on fresh surfaces; crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; mottles 1-5 cm

in diameter, more or less spherical in shape, better lithified than surrounding soil, have smaller peds and hold moisture in their ped fractures longer than surrounding soil; green mottles irregularly shaped; surface of slope appears granular; contact with lower unit gradational; interpreted to be a Bt soil horizon with angular blocky peds. *2.9*

14. Mudstone, light red on weathered surfaces, brick red with rare 1- to 3-cm-diameter, aqua-green mottles on fresh surfaces; crumbles to 1-cm-diameter, angular-blocky structures defined by slickensides; 6.0 m above base a layer of concentrated green, irregularly shaped mottles, up to 0.1 m in diameter; mottles commonly elongate indicating possible root origin; contact with underlying unit abrupt; interpreted to be a Bt soil horizon with angular blocky peds. *9.0*

13. Sandstone, hematite stained on weathered surfaces, white with red mottling on fresh surfaces, fine-grained, moderately sorted, some feldspar and minor amounts of muscovite, a green mineral, and a black mineral; horizontally laminated, laminae 1 mm to 0.3 cm thick, cleaves well along laminations. *0.6*

12. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces; sandy, poorly lithified, slope forming; sand predominantly loosely consolidated, relict bedding present; mottling appears concentrated along bedding planes; interpreted to be a C soil horizon with only slightly altered parent material. *3.6*

11. Conglomerate and sandstone. Conglomerate yellow on weathered and fresh surfaces; clasts angular, poorly sorted, generally coarsen downward, predominantly shale supported by a matrix of medium-grained sandstone. Sandstone, similar to underlying unit; lenses laminated in 1- to 1.5-cm-thick layers, bedded in small scale sinusoidal tabular cross-beds; grades downward from coarse- to medium-grained; contact with underlying unit erosional. *1.4*

10. Sandstone, white on weathered and fresh surfaces, well lithified, medium-grained, moderately sorted, with feldspar and trace of mica; grains angular to sub angular; cross-bedded with low angle laminae 1-2 cm thick and sets 10 cm thick, cleaves along laminations; contact with lower unit erosional. *0.1*

9. Mudstone, light purple grading to light red downward on weathered surfaces, purplish red grading to brick red on fresh surfaces; crumbles to platy structures grading to angular-blocky structures downward, structures average 1 cm diameter, defined by slickensides; contact with underlying unit sharp; interpreted to be a grading from a Bs or E soil horizon with platy peds downward to a Bt soil horizon with angular blocky peds. *0.1*

8. Sandstone, brown on weathered surfaces, red and white mottled on fresh surfaces, sinusoidal tabular-planar cross-bedding near top, lower down alternating green, lavender, and yellow beds on fresh surfaces, beds repeated in no particular order; medium-grained, moderately sorted with feldspar and trace amount of mica, grains angular to subangular, cross-bedded, laminae 1-2 cm thick, sets 35 mm thick; small (0.35 m) sinusoidally cross-bedded sets interbedded with thicker sets, thicker sets angular tabular cross-bedded, appear nearly horizontal, lower part of unit obscured by slope, no splitting planes; light green beds slightly hygroscopic. *6.7*

7. Mudstone, light red grading to light purple upward on weathered surfaces, brick red grading to purplish red on fresh surfaces; crumbles to angular-blocky structures grading to platy structures

upward, structures average 1 cm across, defined by slickensides; contact with underlying unit sharp; concentration of botryoidal carbonate nodules on the surface; interpreted to be grading downward from a Bsc or Ec soil horizon with platy peds and nodules to a Btc soil horizon with angular blocky peds and nodules. *10.7*

6. Mudstone, light green on weathered surfaces and green with 5% sand and pebble-sized red mudstone clasts on fresh surfaces; poorly-lithified, slope forming, clayey, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; contact with lower unit apparently gradational; interpreted to be a Bt soil horizon with angular blocky peds. *0.2*

5. Mudstone, light red on weathered surfaces and brick red on fresh surfaces, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; contact with underlying unit gradational, botryoidal carbonate nodules concentrated on surface; interpreted to be a Bt soil horizon with angular blocky peds. *6.1*

4. Sandstone, grades from lavender to yellow to orange to red on weathered surfaces, on fresh surfaces predominantly red with some

white lenses, moderately well lithified, medium-grained, well sorted, with feldspar and trace amounts of magnetite and mica; grains angular to subangular; 7-cm-thick angular -trough cross-beds; weathers to distinctive "toadstool" appearance. *4.3*

3. Sandstone, lavender on weathered surfaces, alternating beds white to light green and light purple to red on fresh surfaces, moderately well lithified, grains well sorted, angular to sub-angular grains of quartz, feldspar, and green and black minerals, carbonate cement; very low-angle cross-beds, likely trough; contact with underlying unit gradational; petrified trees at top of unit oriented N25°E, N21°W, N65°E. *1.1*

2. Sandstone and conglomerate. Sandstone, dark brown on weathered surfaces, alternating beds of white and light purple to red on fresh surfaces, resistant ledge-former; grains angular to subangular, medium-grained, well sorted, quartz, feldspar, and green mineral; cement is slightly reactive to dilute HCl; cross-beds stacked in sets with an average thickness of 0.23 m, lenses of smaller 2-cm-thick sets interbedded, cleaves easily along bedding planes; erosional contact with underlying unit, fills channel scour; in base of channel, resistant, pebbly sandstone, predominantly red

mudstone, with large rip-up clasts of sandstone, and 3-cm-thick, cross-bedded, sandstone layer with same composition as rest of sandstone in unit. Conglomerate, well lithified, ledge former; clasts poorly sorted, 1 mm to 4 cm in diameter, predominantly calcite with some quartz and rip-up clasts of siltstone, well rounded, spheroidal to sub-spheroidal; matrix supported, composed of fine-grained sandstone; 2-4 mm layers of sandstone interbedded with layers of conglomerate, discontinuous, weathers brown with pitting between clasts, on fresh surfaces washed out shades of red, gray, brown, and green. *1.6*

1. Mudstone, light red on weathered surfaces and purple to red on fresh surfaces with rare green mottles, poorly exposed, some slump blocks, clayey with few sand grains, crumbles to granular structures less than 1 mm diameter; carbonate nodules 1cm to 0.5 m in diameter, abundance of nodules decreases downward; weathers to slope covered with mostly fragmented calcite nodules, whole nodules have botryoidal appearance; interpreted to be an Ac soil horizon with granular peds and nodules; 10.1 from top of unit, there is a 5-cm-thick, grain-supported, poorly sorted, calcite-cemented coarse-grained sandstone layer with subangular grains. *21.6*

Total of Petrified Forest Member 74.1

Bluewater Creek Member

5. Sandstone, purple, red, and/or brown on both fresh and weathered surfaces, resistant, fine-grained, calcite cemented, cross-bedded with laminae 1mm thick, stacked in 0.1- to 1.0-m-thick beds; symmetrical ripples on every bedding surface; cleaves easily along laminations; contact with underlying unit erosional, channel form. *1.5*

4. Interbedded clay and sandstone, both reddish brown on weathered surfaces, gray on fresh surfaces. Clay beds 0.25 m thick, crumbles to angular-blocky structures 2-3 cm in diameter, interpreted to be a Bt soil horizon with angular blocky peds. Sandstone, laminae 1 mm thick, beds 0.1 m thick, resistant, fine-grained, calcite cemented. *1.0*

3. Mudstone, light green on weathered surfaces, green on fresh surfaces, grades upward to yellow mudstone, light yellow on weathered surfaces, brown on fresh surfaces, and grades laterally to red mudstone, crumbles to granular structures; botryoidal to oblong spheroidal calcite nodules 1 to 20 cm in diameter, spheroidal

nodules increasingly concentrated in lower portion of unit average 1.5 x 1.0 cm; weathers to slope covered in fragmented calcite nodules; contact with underlying unit gradational, interpreted to be an Ac soil horizon with granular peds and nodules. *7.4*

2. Pebble conglomerate, gray on weathered surfaces; clasts angular to subangular, oblate spheroids, average 5 x 2 cm, up to 20 cm diameter, consisting of gray, silty limestone, dark gray siltstone, yellow siltstone, and carbonate nodules similar to soil nodules; matrix of medium- to coarse-grained, poorly sorted, calcite-cemented, clast-supported sandstone; clasts imbricated, paleocurrent direction to the north; conglomerate occupies channel form which pinches out laterally; contact with underlying unit erosional. *0 - 4.2*

1. Mudstone, light red on weathered surfaces, purple to red on fresh surfaces; poorly exposed, mudstone varies in thickness and is completely absent when the pebble conglomerate is thickest; clayey, few sand grains, crumbles to 1-mm-diameter, angular-blocky structures; calcite nodules 1 cm to 0.5 m diameter, decreasing in abundance downward; weathered to slope covered in commonly fragmented calcite nodules, whole nodules have

botryoidal appearance; interpreted to be a Btc soil horizon with angular blocky peds and nodules. *0 - 4.2*

Total of Bluewater Creek Member *14.1*

Monitor Butte Member

4. Mudstone, light green on weathered surfaces, green on fresh surfaces, clayey, crumbles to platy structures 1 mm to 0.5 cm-diameter, contains 1-cm to 0.2-m-diameter calcite nodules with botryoidal appearance; weathers to slope covered in mostly fragmented calcite nodules; interpreted to be a Bsc soil horizon with platy peds and nodules. *2.2*

3. Mudstone, light red on weathered surfaces, purple to red on fresh surfaces, poorly exposed, clayey, few sand grains, crumbles to 1 mm diameter angular-blocky structures; 1-cm- to-0.5-m-diameter, botryoidal-appearing, calcite nodules decreasing in abundance downward; weathers to slope covered in mostly fragmented calcite nodules, interpreted to be a Bt soil horizon with angular blocky peds and nodules. *2.8*

2. Covered. *1.7*

1. Interbedded mudstone, siltstone, and sandstone, hematite stained or mottled red and green on weathered surfaces, gray green on fresh surfaces; mudstone and siltstone micaceous and laminated; sandstone, fine-grained, quartz-rich, micaceous, beds thin to 1 mm, in upper part ripples dominate with intervals of cross-bedding in 0.1m sets. *1.3*

Total of Monitor Butte Member *8.0*

Shinarump Member

1. Sandstone with alternating laminations of red and white on weathered surfaces, light green with red polka dots on fresh surfaces, resistant, cliff-former, composed of coarse- to medium-grained, well sorted, subangular grains with rare well-rounded pebbles and silica cement; laminations 1 mm thick, bedded in sinusoidal-trough cross-beds stacked in sets averaging 10-15 cm thick with a maximum thickness of 0.6 m; horizontal laminae between sets, beds dip 12 degrees and strike S86°W, cleaves along laminations; exposed predominantly in active stream channels. *2.5*

Total of Incomplete Shinarump Member *2.5*

Total of Incomplete Chinle Exposure 136.3

Base of section covered

Moenkopi Formation

1. Mudstone, brick-red, horizontally bedded.

Badger Butte Stratigraphic Column

Measured about 0.85 km southwest of the Wolverine Petrified Wood area trailhead, on the northeastern side of the southern mound of Badger Butte from approximately 37° 48'10" N, 111° 12'41"W to 37° 48'03"N, 111° 13'09"W.

Wingate Formation

1. Sandstone, yellow on weathered and fresh surfaces, well sorted, medium-grained, quartz-rich with large-scale cross-beds; resistant, cliff-former; contact with underlying member sharp, but does not appear erosional.

Top of section, top of formation.

Chinle Formation

Church Rock Member

2. Sandstone, interbedded green to white and dark red on weathered and fresh surfaces, fine-grained, generally structureless with some convoluted bedding; matrix-supported stringers or lenses of white gravels with clasts coarse sand to 7.0 cm diameter, angular, and poorly sorted; less resistant than Wingate unit, but cliff forming. *0.9*

1. Mudstone, red and aqua green mottled on weathered surfaces, light red and green mottled on fresh surfaces, blocky, cliff-forming; green mottles round and regularly shaped in the lower exposures of the unit, root-like and horizon-forming near the top, 5–cm-thick horizons; clay nodules concentrated in layers occur throughout the unit, average 1x2 cm, have a stacked appearance and increase in size upward until forming columnar shapes defined by root traces; above this, nodules decrease in size and concentration almost 100%; gradational contact with the underlying unit, interpreted to be a Btc soil horizon with subangular blocks and nodules. *1.2*

Total of Church Rock Member *2.1*

Owl Rock Member

8. Cliff. *16.0*

7. Mudstone, white to light green and light red, mottled on weathered surfaces, grades upward to red with green mottles on weathered and fresh surfaces, well cemented, angular-blocky with block structures up to 0.3m, blocks decrease in size upward eventually resulting in small slopes; blocks more layered and horizontal near top of red portion of the unit; blocks rounded on

weathered surfaces; small slope where mudstone transitions from light green to red in unit; mottles round, regularly shaped, up to 5 cm in diameter; top 0.5 m of exposure green mudstone with larger, rounded blocks; red to green sequence repeats twice; interpreted to be an A soil horizon that grades downward to a Bt horizon; root traces present. *4.7*

6. Cliff. *7.0*

5. Conglomerate and mudstone. Conglomerate, 1.0 m thick, massive, clasts quartzite and rip-up clasts of shale up to 3 cm diameter; matrix supported, matrix coarse sand; reacts to dilute HCl when powdered. Mudstone, red with green mottles on weathered and fresh surfaces, 5-cm-diameter angular-blocky structures increase in size and resistance downward; nodules, oblong, react slightly to dilute HCl and appear crystalline on fresh surfaces, form a maximum of 50% of the unit, increase in abundance downward, average 1 x 2cm; mottles round and regularly shaped, up to 5 cm diameter; contact with underlying mudstone erosional; interpreted to be an A soil horizon grading downward to a Btc soil horizon. *2.3*

4. Cliff *3.7*

3. Mudstone, red with green mottles on weathered and fresh surfaces, well cemented, 5-cm-diameter angular-blocky structures increasing in size and resistance downward; mottles round, regularly shaped, up to 5 cm in diameter; interpreted to be an A soil horizon grading downward into a Bt soil horizon. *1.5*

2. Cliff. *1.0*

1. Mudstone, white to light green and light red mottled on weathered surfaces, well cemented, reacts slightly to dilute HCl with 3-cm- to 0.15-m-diameter angular-blocky structures, rounded on weathered surfaces; 0.8 m above base of unit 0.1-m-diameter chert nodules increasing in abundance upward, appear concentrically formed, oblong or joined to form peanut shapes; root traces 0.8 m above base of unit; interpreted to be a Btkq soil horizon. *1.9*

Total of Owl Rock Member *38.1*

Petrified Forest Member

16. Mudstone, light red on weathered surfaces and brick red with reduction spots on fresh surfaces, crumbles to 1-cm- to 1.2-cm-diameter angular-blocky structures defined by slickensides; 1-5-cm-diameter reduction spots; interpreted to be a Bt soil horizon. *13.0*

15. Mudstone, light red on weathered surfaces and brick red with angular or oval-shaped green reduction spots on fresh surfaces, sandy, poorly-lithified, slope forming, crumbles to angular-blocky, poorly formed structures; reduction spots up to 0.1m in diameter, increase in abundance upward forming a layer near the top of the exposure; interpreted to be a young Bt soil horizon with some qualities of a C soil horizon. *2.3*

14. Sandstone and conglomerate. Sandstone, dark brown on weathered surfaces, laminated in cm thick layers; sinusoidal tabular-planar cross-beds 0.05 to 0.1m thick; lenses of resistant, cliff-forming sand pinch out laterally; beds coarsen downward. Conglomerate, clast-supported in four 0.25-m-thick beds; clasts, angular, less than 1 cm diameter, consist of rip-up clasts of shale, sandstone, and mudstone with limited amounts of limestone;

matrix fine-grained sandstone; calcite cemented; conglomerate less well lithified than sandstone layers and forms slopes or alcoves. *4.1*

13. Sandstone, brown on weathered surfaces, alternating green, lavender, and yellow beds on fresh surfaces, repeated in no particular order, 4.3 m from top, mustard yellow color dominant, well-lithified, medium-grained, moderately sorted with angular to subangular grains consisting of limited feldspar and trace amounts of mica; light green beds slightly hygroscopic; indeterminately cross-bedded, laminae 1-2 cm thick, sets 0.5 to 1.0 m thick, smaller sets (0.35 m thick) with sinusiodal cross-beds interbedded with larger sets, larger sets likely angular tabular-planar, appear nearly horizontal; lower part of unit obscured; does not cleave easily. *5.3*

12. Sandstone, dark brown on weathered surfaces, alternating green, lavender, and yellow beds on fresh surfaces, beds repeat in no particular order but the mustard yellow color is dominant, well-lithified, medium-grained, moderately sorted with angular to subangular grains consisting of limited feldspar and trace amounts of mica; light green beds slightly hygroscopic; laminated in cm-thick layers with angular tabular-planar cross-beds; beds fine upward; discontinuous lenses of resistant sandstone form cliffs. *0.7*

11. Sandstone, loosely lithified, clayey material in upper 7.7 m, sandy clay crumbles to platy structures up to 1 cm diameter, grades downward to fine- to medium-grained, poorly to moderately sorted sand with subangular grains composed of limited feldspar and trace amounts of mica with rare rip-up clasts of red clay; lavender on weathered surfaces, alternating white and lavender on fresh surfaces, laminated in layers less than 1 cm thick; laminae stacked in cross-beds; more lithified, carbonate-cemented layers of the same material 0.1m thick at 2.0 m, 4.6m, and 7.7 m above the base of the unit; 5.0-cm-thick white, laminated, silty layer 3.7 m above the base of the unit reacts moderately to dilute HCl. *7.7*

10. Sandstone, brown on weathered surfaces, alternating bands of white and red with reduction spots on fresh surfaces, medium-grained, laminated in 1-cm-thick layers, cross-bedded in 0.1m thick sets that truncate lower sets, likely angular tabular-planar; contact with underlying unit erosional. *0.6*

9. Mudstone, light red on weathered surfaces, dark red and green mottled on fresh surfaces, crumbles to angular-blocky structures 0.2-1 cm in diameter; mottles irregularly shaped, up to 1cm in

diameter, concentration of green increases upward but not to a solid green; interpreted to be a Bt soil horizon. *5.0*

8. Mudstone, light red and light green mottled on weathered surfaces, dark red and green mottled on fresh surfaces, crumbles to angular-blocky structures 0.5-2 cm in diameter; mottles irregularly shaped, concentration of green increases upward; contact with lower unit gradational; interpreted to be a Bt soil horizon. *2.6*

7. Mudstone, light red on weathered surfaces, dark red and green mottled on fresh surfaces, crumbles to angular-blocky structures 0.2-1 cm in diameter; mottles irregularly shaped, up to 5 cm in diameter; concentration of green increases upward; interpreted to be a Bt soil horizon. *2.5*

6. Mudstone, light red and light green mottled on weathered surfaces, dark red and green mottled on fresh surfaces, crumbles to angular-blocky structures 0.5-2 cm in diameter; mottles irregularly shaped; concentration of green increases upward; interpreted to be a Btc soil horizon. *2.8*

5. Mudstone, light red on weathered surfaces, brick red on fresh surfaces, crumbles to 1-cm-diameter, angular-blocky structures defined by slickensides, weathers to slope covered in commonly fragmented calcite nodules; whole nodules have a botryoidal appearance; contact with underlying unit gradational; underlying sandstone a likely protolith; interpreted to be a Btc soil horizon. *1.3*

4. Sandstone, red on both weathered and fresh surfaces with some white lenses, moderately well lithified, fine-grained, well sorted, cross-bedded with angular tabular-planar sets with average thickness of 7 cm, magnetite in the sandstone defines cross-beds; sandstone cut by 0.5-to 2-cm-thick veins of sparry calcite with a stacked or layered appearance; interbedded with the sandstone are 5-cm-thick clayey beds. *2.0*

3. Sandstone and conglomerate. Sandstone, light pink to brown in color on fresh and weathered surfaces (brown color dominant at top of unit), moderately well lithified, slope-former, medium-grained, well sorted clasts of angular to subangular quartz, feldspar, and green and black minerals, carbonate cemented; very low-angle cross-beds, likely trough, defined by black minerals; petrified trees 0.35 m above base of unit, oriented N25°E,

fragmented, 0.9, 0.7, 0.8, 0.7, 0.15, 1.5, and 1.0 m diameter, 9.0, 7.0, 25.0, 8.0, and 12.0 m in length; 0.3-m-thick resistant sand layer present at base of unit, reacts to dilute HCl when powdered and is likely dolomite cemented; layer fills channel form and is discontinuous; contact with lower unit is erosional. Conglomerate, 0.2 m thick, fills channel at the base of unit and is discontinuous; clasts up to 1 cm diameter composed predominantly of red sandstone, some clayey siltstone and angular-platy, rip-up clasts of unit 3; matrix sandy with a composition similar to the underlying unit except with a higher black mineral content, calcite-cemented, clast-supported, fines upward, light red on weathered surfaces and dark red on fresh surfaces, appears horizontally bedded in beds over 1 cm thick; surface appears porous as if some clasts have preferentially weathered out. *1.0*

2. Sandstone, white grading to lavender laterally on fresh and weathered surfaces, moderately-well lithified, medium-grained, moderately sorted, composed of angular to subangular grains with limited feldspar and trace amounts of muscovite defining very low-angle trough cross-bedding, reacts weakly to dilute HCl, not hygroscopic. *2.7*

1. Mudstone, purple or red on both fresh and weathered surfaces, crumbles to angular-blocky structures which grade downward to platy structures; mustard yellow, silty material appears to fill in cracks in the unit; rare thin-bedded mudstones; weathers to a slope covered in commonly fragmented calcite nodules; whole nodules have a botryoidal appearance; lower 12.0 cm of the unit contains yellow to brown calcite nodules averaging 8 x 15 cm, form layers, and decrease in concentration downward; contact with the underlying unit is poorly exposed; interpreted to be a C soil horizon with platy peds grading to a Btc soil horizon with angular blocky peds and nodules. *13.0*

Total of Petrified Forest Member *66.6*

Bluewater Creek Member

2. Sandstone, purple, red, and/or brown in color on both fresh and weathered surfaces, resistant, fine-grained, laminated in 1-mm-thick layers with symmetrical ripples apparent on every bedding surface; layers are stacked in cross-beds 0.1 m to 1.0 m thick; carbonized fossil leaves present; fills channel form and is discontinuous; contact with underlying unit erosional. *0-5.0*

1. Mudstone, light red on weathered surfaces, dark red with green mottles on fresh surfaces, crumbles to angular-blocky structures 1 mm in diameter; includes laminations of sandstone; truncated by overlying sandstone unit; interpreted to be a Bt soil horizon with angular blocky peds. *0-5.0*

Total of Bluewater Creek Member 5.0

Monitor Butte Member

4. Interbedded mudstone, sandstone, and conglomerate. Sandstone and mudstone, light green on fresh surfaces, red to pink on weathered surfaces; siltstone mica-rich; sandstone medium-grained, cross-beds 0.3 to 0.6 m thick, increases in abundance upward, contains symmetrical ripples. Conglomerate, massive bedded lenses, poorly sorted, clasts of chert, siltstone, and sandstone with limited amounts of organic material. *12.5*

3. Covered. *1.5*

2. Mudstone and sandstone, interbedded, hematite stained or mottled red and green on weathered surfaces, gray green on fresh surfaces. Mudstone, micaceous, discontinuous. Sandstone, increases downward, fine-grained, micaceous and quartz-rich, beds

1 mm thick and rippled at top of exposure, separated by intervals of 0.1-m-thick cross-bedding; base of unit dominated by cross-bedded sandstone; contact with lower unit erosional, channel fill. *0.3-1.0*

1. Siltstone, mudstone, and sandstone, interbedded, hematite stained or mottled red and green on weathered surfaces, gray green on fresh surfaces, rippled, poorly-lithified, slope forming, laterally continuous. Siltstone, laminated, micaceous. Mudstone, laminated, discontinuous. Sandstone, fine-grained, quartz-rich, micaceous; beds 1 mm thick and ripple marked at top of exposure separated by intervals of 0.1-m-high cross-bedding; amounts increase downward; base of unit dominated by cross-bedded sandstone; contact with lower unit erosional, channel fill; variations in the dip of beds. *0.5-1.6*

Total of Monitor Butte Member *14.8-16.9*

Shinarump Member

3. Sandstone, alternating laminations of red and white sand on weathered surfaces, light green with red polka dots on fresh surfaces, weathers to cliffs and caves, coarse- to medium-grained, well sorted, composed of subangular quartz grains, silica cemented; bedded in a series of sets, first parabolic tabular-planar

cross-beds, then horizontal beds, then sinusoidal tabular-planar cross-beds, then horizontal beds, and then trough cross-beds. *1.2*

2. Sandstone, alternating laminations of red and white sand on weathered surfaces, light green with red polka dots on fresh surfaces, weathers to cliffs and caves, coarse- to medium-grained, well sorted, composed of subangular quartz grains, silica cemented; horizontally bedded. *0.1*

1. Sandstone, alternating laminations of red and white sand on weathered surfaces, light green with red polka dots on fresh surfaces, weathers to cliffs and caves, coarse- to medium-grained, well sorted, composed of subangular, quartz grains, silica cemented; sinusoidal-trough cross-beds are on average 10-15 cm thick but may reach as much as 1 m thick, where one set ends, there is commonly a series of horizontal laminae deposited before the next set begins, there are rare well rounded pebbles in the sandstone; cross-beds dip N70°W. *1.0*

Total of Incomplete Shinarump Member *2.3*

Total of Incomplete Chinle Exposure 128.9-131

Base of section covered

Moenkopi Formation

1. Mudstone, brick red, horizontally bedded.

Circle Cliffs Stratigraphic Column

Measured 0.7 km southeast of the Wolverine Petrified Wood area trailhead, 0.25 km south of the road, on the northernmost slopes of the bench which lies between Badger Butte and Lizard Butte and has the name Circle Cliffs written on it on the Pioneer Mesa Quadrangle, 7.5-minute series, 1987, from approximately 37° 48'11" N, 111° 11'55"W to 37° 47'50"N, 111° 12'06"W.

Wingate Formation

1. Sandstone, yellow on weathered and fresh surfaces; well sorted, medium-grained, quartz rich; large-scale cross-beds; contact with underlying member is sharp, but does not appear erosional, resistant, cliff-former.

Top of section, top of formation.

Chinle Formation

Church Rock Member

2. Sandstone and conglomerate. Sandstone, dark red on weathered and fresh surfaces with rare green to white lenses, fine-grained, generally massive with limited convoluted bedding; not resistant,

but forms cliffs because of protection by Wingate. Conglomerate, rare, matrix-supported stringers or lenses of white gravel, clasts angular, poorly sorted, coarse sand to 7.0 cm diameter. *1.2*

1. Mudstone, red and aqua green mottled on weathered surfaces, light red and green mottled on fresh surfaces; green mottles round and regularly shaped in the lower exposures of the unit, change to root like and horizon-forming near the top of the unit, green horizons average 5 cm thick; clay nodules randomly occurring but also concentrated in layers, average 1x2 cm, have a stacked appearance and increase in size upward until assuming a columnar shape defined by what appear to be root traces, concentration increases upward to almost 100% and size decreases; contact gradational with underlying unit; poorly lithified but forms cliffs because of protection by Wingate sandstone; interpreted to be a Btc soil horizon with subangular blocks and nodules increasing in abundance upward, possibly the early stages of a K soil horizon. *4.6*

Total of Church Rock Member *5.8*

Owl Rock Member

9. Mudstone, red on both weathered and fresh surfaces, contains angular-blocky structures average diameter 1cm, resistant cliff-

former; base of unit obscured by a slope; interpreted to be a Bt soil horizon with angular blocky peds. *4.7*

8. Mudstone, hematite stained on weathered surfaces, light gray-brown on fresh surfaces, well cemented, cliff-former; at top of unit, horizontally laminated with beds 1mm to 7cm thick, average 1cm thick; beds coarsen downward; in lower part of unit rounded blocky structures defined by slickensides, average 1 cm in diameter but up to 7 cm in diameter, angular-blocky structures in lowest 1 m; interpreted to be a Bt soil horizon with subangular blocky peds possibly grading up to a horizontally bedded K soil horizon. *2.2*

7. Covered with mudstone, 2.1 m below top of unit is a 1-m-thick cliff of white mudstone that reacts slightly to HCl when powdered, breaks into 1- to 6-cm-diameter angular-blocky structures that have a vertical, stacked appearance, show no vertical size grading, weather to rounded appearance; interpreted to be a Btk soil horizon with angular blocky peds and a slight reaction to dilute HCl. *7.7*

6. Mudstone, white to light green with pale red mottles on weathered surfaces for top 0.5 m, grades downward to red with green mottles on weathered and fresh surfaces, grades downward

to white to light green and light red mottled on weathered surfaces, well cemented, cliff-former, small slope where mudstone transitions from red to green; layered and horizontal structures near the top, grade downward to angular-blocky structures up to 0.3 m diameter, blocks increase in size downward, larger blocks have greater resistance, structures rounded on weathered surfaces; slight reaction to dilute HCl; red mudstone contains root traces; mottles round, regularly shaped, up to 5 cm diameter; interpreted to be a Btk soil horizon with subangular blocky peds with a slight reaction to dilute HCl grading upward to an A soil horizon. *4.7*

5. Cliff. *6.5*

4. Limestone and mudstone, red with green mottles on weathered and fresh surfaces. Limestone, discontinuous, up to 0.2 m thick. Mudstone, well cemented, breaks into angular-blocky structures up to 5 cm diameter, increase in size and resistance downward, average 1 x 2 cm, oblong, react slightly to dilute HCl on fresh surfaces and appear crystalline, make up to 50% of the soil, increase in abundance downward; mottles round, regularly shaped, up to 5 cm in diameter; interpreted to be a Btc soil horizon with

angular blocky peds and nodules grading upward to a carbonate saturated K soil horizon. *1.4*

3. Mudstone, red with green mottles on weathered and fresh surfaces, well cemented, breaks into angular-blocky structures up to 5 cm diameter, increase in size and resistance downward; mottles round, regularly shaped, up to 5 cm in diameter; interpreted to be a Bt soil horizon with angular blocky peds grading upward to an A soil horizon. *6.3*

2. Mudstone, light red mottled on weathered surfaces, white to light green on fresh surfaces, well cemented, resistant cliff-former; slight reaction to dilute HCl; breaks into angular-blocky structures 3 cm to 0.15 m diameter, rounded on weathered surfaces; chert nodules with average diameter 1.7 cm, decreasing abundance downward, appear concentrically formed, may be oblong or joined to form peanut shapes; interpreted to be a Btqk soil horizon with subangular blocky peds and accumulations of silica and a slight reaction to dilute HCl. *0.9*

1. Cliff. *8.9*

Total of Owl Rock Member *43.3*

Petrified Forest Member

17. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, crumbles to angular-blocky structures 0.5 to 1 cm diameter defined by slickensides; green mottles increase in abundance upward but the unit is lost to a slope before it can be determined if they become dominant; interpreted to be a Bt soil horizon with subangular blocky peds. *1.0*

16. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, crumbles to angular-blocky structures 0.5 to 1 cm diameter, defined by slickensides; green mottles increase in abundance upward until they become dominant near the top of the exposure, irregularly shaped, elongate and root like, reach up to 7.5 x 1 cm diameter; interpreted to be a Bt soil horizon with subangular blocky peds. *2.4*

15. Sandstone, red on weathered surfaces, red with white lenses and mottles on fresh surfaces, moderately well lithified, medium-grained, hygroscopic, laminated in 1-cm-thick layers bedded in wedge-planar cross-beds 0.5 m thick; mottles do not follow the bedding surfaces. *3.8*

14. Sandstone, alternating red and green beds on fresh surfaces, unlithified; fine- to medium-grained, well sorted; near top of unit some platy structures 0.2 to 1 cm diameter but bedding retained; beds 0.2 to 4.5 cm thick; unit 12 may be the protolith for this unit. *2.0*

13. Sandstone, similar to unit 12, calcite cemented, resistant, coarse- to very coarse-grained, some limestone pebbles less than 5 mm, angular tabular-planar cross-bedded, discontinuous. *0.1*

12. Sandstone, alternating red, white, lavender, and yellow beds with reduction spots and/or mottling on fresh surfaces, repeat in no particular order, unlithified, medium-grained, moderately sorted, composed of angular to subangular grains with limited feldspar and trace amounts of mica; 0.1-2 m thick, angular tabular-planar cross-beds. *5.8*

11. Mudstone and conglomerate. Mudstone, sandy, lavender on weathered surfaces, red to purple on fresh surfaces with green mottles and/or reduction spots, reduction spots and mottles circular, 0.5 to 2 cm diameter; sandy layers contain less than 5% of a black mineral; at top clay dominant and unit crumbles to granular

structures, downward sand increases and unit crumbles to platy structures, relict bedding present; interpreted to be a C soil horizon, slightly weathered bedrock, grading upward to an A soil horizon. Conglomerate, hematite stained on weathered surfaces, light green on fresh surfaces, resistant, clasts moderately to poorly sorted, angular, supported in a matrix of medium-grained sandstone, composed of rip-up clasts from underlying red mudstone layers with limited limestone clasts, less than 1 cm diameter; reverse grading; slight reaction to dilute HCl; where conglomerate clasts are small, clasts cross-bedded with coarse sand. *3.0*

10. Sandstone, well lithified cliff-former, medium- to coarse-grained, dolomite-cemented, laminated in 1-mm-thick layers grouped into 0.5-cm-thick layers bedded in 0.2-m-thick sinusoidal tabular-planar cross-beds (nature of cross-beds questionable due to difficult exposure); rib and furrow structures 0.5 to 2 cm thick, rare 1-cm-thick pebble stringers composed of same gravel as the underlying conglomerate; 1-m-wide petrified wood fragments present in small cross beds; contact with underlying unit erosional. *0.5*

9. Conglomerate, hematite stained on weathered surfaces, light green on fresh surfaces, resistant; clasts moderately to poorly

sorted, angular, supported in a matrix of medium-grained sandstone, composed of rip-up clasts from underlying red mudstone layers with limited limestone clasts, less than 1 cm diameter; reverse graded; slight reaction to dilute HCl; contact with underlying unit obscured but is most likely gradational. *0.8*

8. Mudstone, sandy, lavender on weathered surfaces, red to purple on fresh surfaces with green mottles and/or reduction spots, reduction spots and mottles circular, 0.5 to 2 cm diameter; sand contains less than 5% of a black mineral; at top clay dominant and unit crumbles to granular structures; downward sand increases and unit crumbles to platy structures containing relict bedding; interpreted to be a C soil horizon grading upward to an A soil horizon. *5.9*

7. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, crumbles to angular-blocky structures defined by slickensides 0.2 to 0.5 cm diameter; contact with underlying unit gradational, underlying sandstone likely protolith; interpreted to be a Bt soil horizon with subangular blocky peds. *5.4*

6. Sandstone and mudstone, red on weathered and fresh surfaces with some white lenses, moderately well lithified, fine-grained, well sorted; angular tabular-planar cross-beds average 7 cm thick, magnetite defines cross-beds; unit cut by 0.5- to 2-cm-thick veins of sparry calcite which commonly have a stacked or layered appearance; 2.0 m from base of the unit is a 4.5-cm-thick more resistant layer, green with red mottles on fresh surfaces. Mudstone, interbedded with sandstone in 5-cm-thick beds. 4.9

5. Conglomerate, red on weathered and fresh surfaces; dolomite cemented, angular tabular-planar cross-beds. *0.3*

4. Sandstone and conglomerate. Sandstone, yellow grading to white and lavender downward on weathered surfaces, moderately-well lithified, medium-grained, moderately sorted, composed of angular to subangular grains with limited feldspar and trace amounts of muscovite, biotite, and a green mineral, reacts weakly to dilute HCl, not hygroscopic. Conglomerate, interbedded as lenses and one layer, variably resistant, dolomite cemented, bedded in angular tabular-planar cross-beds; lenses 0.25 m thick; contact with underlying unit is either erosional, filling channel forms, or gradational. *1.6*

3. Conglomerate, dark gray to brown on both weathered and fresh surfaces; clasts angular to subangular, oblate spheroids, average 5 x 2 cm, maximum 20 cm long, composed of beige siltstone, black shale, brown limestone, and rip-up clasts of other conglomerates and red clay; matrix-supported, matrix coarse-grained, poorly sorted sandstone, slightly porous on weathered surfaces; calcite-cemented; structure is undeterminable; discontinuous; fills channel cut into underlying unit. *0.4*

2. Mudstone, light purple on weathered surfaces, purple to red with green mottles on fresh surfaces, color grades to red downward, then back to purple again, crumbles to angular-blocky structures 0.2 to 0.5 cm diameter; calcite nodules 1 cm to 0.5 m diameter, increase in abundance upward; whole nodules have a botryoidal appearance; weathers to slope covered in mostly fragmented calcite nodules; contact gradational with lower unit; interpreted to be a Btc soil horizon with subangular blocky peds and nodules that increase in abundance upward. *16.8*

1. Mudstone, light green on weathered surfaces, grayish green on fresh surfaces, crumbles to angular-blocky structures 1 mm to 0.5

cm diameter; red mottles increase downward; weathers to a slope of 17 degrees, slope has a distinctive granular appearance which forms on top of a popcorn-like surface; contact with underlying unit is gradational; interpreted to be a Bt soil horizon with subangular blocky peds. *5.8*

Total of Petrified Forest Member *60.5*

Section Offset East 400m

Bluewater Creek Member

2. Sandstone, dark brown on weathered surfaces, alternating beds of white and light purple to red on fresh surfaces, resistant cliff-former, medium-grained, well sorted, grains angular to sub angular composed of quartz, feldspar, and green minerals; cement has slight reaction to dilute HCl; beds horizontal and wavy, 0.1 mm to 0.5 cm thick, discontinuous; contact with underlying unit erosional, channel fill. *2.4*

1. Mudstone, light red, light green, and light purple on weathered surfaces, dark brown with green granules on fresh surfaces, crumbles to 1-mm-diameter angular-blocky structures; nodules oblong, white, calcite, 0.5 cm to 1.5 cm diameter; weathers to

slope; interpreted to be a Btc soil horizon with subangular blocky peds and nodules. *5.0*

Total of Bluewater Creek Member *7.4*

Monitor Butte Member

1. Siltstone and sandstone, hematite stained or mottled red and green on weathered surfaces, gray green on fresh surfaces; unit susceptible to slumping, strikes and dips may be unreliable. Siltstone, micaceous. Sandstone, fine-grained, quartz-rich, micaceous; beds at top 1 mm thick, rippled, mini-cross-bedded in sets 0.5 cm thick, rare intervals of cross-bedding in 0.1-m-thick sets, ripples decrease in abundance downward. *9.6*

Total of Monitor Butte Member *9.6*

Shinarump

1. Sandstone and conglomerate. Sandstone, alternating laminations of red and white sand on weathered surfaces, light green with red polka dots on fresh surfaces, coarse- to medium-grained, well sorted, grains subangular, primarily quartz, silica cement; sinusoidal-trough cross-beds stacked in sets that average 10-15 cm thick but are as much as 0.6 m thick, horizontal laminae between sets; rare well-rounded pebbles; 0.7 m from base of unit, coarse-

grained sandstone lenses 3 cm to 0.1 m thick fill scours into the medium-grained sandstone; cross-bedded; rare pebbles; beds ungraded; beds dip 8 degrees, S20°W. Conglomerate, 0.7 m above base of unit, occurs as 3-cm- to 0.1-m-thick lenses filling scours into the sandstone, poorly sorted; clasts primarily well-rounded quartzite with angular shale and siltstone, maximum diameter 1.5 cm; massive. *2.7*

Total of Incomplete Shinarump Member *2.7*

Total of Incomplete Chinle Exposure *129.3*

Base of section covered

Moenkopi Formation

1. Mudstone, brick-red, horizontally bedded.

Lizard Butte Stratigraphic Column

Measured 1.6 km east-southeast of the Wolverine Petrified Wood Area trailhead, 0.1 km south of the road, on the northernmost slope of the butte just north-northwest of Little Bown Bench, from approximately 37° 48'07" N, 111° 11'25"W to 37° 47'46"N, 111° 11'32"W.

Wingate Formation

1. Sandstone, yellow on weathered and fresh surfaces, well sorted, medium-grained, quartz-rich; large-scale cross-beds; contact with underlying member is sharp, but does not appear erosional; resistant, cliff-former.

Top of section, top of formation.

Chinle Formation

Church Rock Member

2. Sandstone and conglomerate. Sandstone, dark red on weathered and fresh surfaces, rare white lenses, poorly lithified but forms cliffs because of protection by Wingate, fine-grained, generally massive with limited convoluted bedding. Conglomerate, matrix supported stringers or lenses of white gravel; gravel clasts coarse sand to 7.0 cm diameter, angular, poorly sorted. *0.5*

1. Mudstone, red and green mottled on fresh and weathered surfaces, blocky, poorly lithified but forms cliffs because of protection by Wingate, non calcareous, cherty; irregularly shaped nodules have stacked appearance, vary from 1 to 5 cm; contact gradational with underlying unit; interpreted to be a Btq soil horizon with subangular blocky peds and silica accumulations. *3.0*

Total of Church Rock Member *3.5*

Owl Rock Member

12. Cliff, poor exposures of green then red mudstone. *10.2*

11. Mudstone, white to light green and light red mottled on weathered surfaces, well cemented, cliff-former; ribbon-like layers 2-5 cm thick throughout unit. *1.6*

10. Cliff. *7.1*

9. Mudstone, white to light green and light red mottled on weathered surfaces, well cemented, cliff-former; crumbles to angular-blocky structures defined by slickensides that vary in size; nodules asymmetrical, calcite, 2-3 cm diameter; interpreted to be a Btc soil horizon with angular blocky peds and nodules. *3.0*

8. Cliff. *1.5*

7. Mudstone, white to light green and light red mottled on weathered surfaces, well cemented, cliff-former, crumbles to angular-blocky structures defined by slickensides 5 cm and larger in diameter; interpreted to be a Bt soil horizon with angular blocky peds. *1.7*

6. Cliff. *5.6*

5. Limestone and mudstone. Limestone composes top 0.15 m of unit, white on fresh surfaces. Mudstone, hematite stained on weathered surfaces, light green and white mottled on fresh surfaces, well cemented, cliff-former; crumbles to angular-blocky structures defined by slickensides; interpreted to be a Bt soil horizon with angular blocky peds grading upward to a carbonate saturated K soil horizon. *0.3*

4. Cliff. *0.7*

3. Mudstone, hematite stained on weathered surfaces, light green and white mottled on fresh surfaces, well cemented, cliff-former, crumbles to angular-blocky structures defined by slickensides; nodules, asymmetrical, calcite, 2-3 cm diameter, stacked in some places and make up to 25% of the soil; interpreted to be a Btc soil horizon with angular blocky peds and nodules. *0.7*

2. Cliff. *6.0*

1. Mudstone, white to light green and light red mottled on weathered surfaces, well cemented, crumbles to angular-blocky structures defined by slickensides 0.5 cm to 2 cm diameter; nodules, chert, 1-3 cm diameter, increase in abundance upward, appear concentrically formed, may be oblong or joined to form peanut shapes; no carbonate present; interpreted to be a Btq soil horizon with angular blocky peds and silica concentrations. *1.6*

Total of Owl Rock Member *40.0*

Petrified Forest Member

20. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, crumbles to 1-mm- to 0.5-cm-diameter angular-blocky and platy structures defined by slickensides; interpreted to be a Bt soil horizon with angular blocky peds. *4.6*

19. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, poorly lithified, slope-former; large amount of sand; interpreted to be a C soil horizon with slightly weathered parent material. *17.4*

18. Sandstone, hematite stained on weathered surfaces and white on fresh surfaces, fine-grained, moderately sorted, composed of

limited feldspar and trace amounts of muscovite, a green mineral, and a black mineral; horizontally laminae 1 mm to 0.3 cm thick, cleaves easily along laminations. *0.4*

17. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; interpreted to be a Bt soil horizon with angular blocky peds. *4.7*

16. Sandstone, alternating red, white, lavender, and yellow beds on fresh surfaces, repeat in no particular order, red beds have reduction spots and/or mottling, unlithified; beds 0.1-2 m thick; medium-grained, moderately sorted, angular to subangular grains with feldspar and trace amounts of mica; angular tabular-planar cross-beds 0.1 to 0.5 m thick. *4.0*

15. Mudstone and conglomerate, light red on weathered surfaces, brick red with green mottles on fresh surfaces. Mudstone, crumbles to 1-mm-diameter platy structures defined by slickensides, weathers to slope covered in carbonate nodules; contact with underlying unit obscured, likely gradational; interpreted to be a Bs(c?) soil horizon with platy peds nodules. Conglomerate, clasts

consist of rip-up clasts from underlying red soil layers and limited carbonate, clasts 1 cm to 4 cm diameter; poorly sorted, supported in a matrix of medium-grained sandstone. *0.2*

14. Sandstone, brown on weathered surfaces, red and white mottled on fresh surfaces, poorly lithified, slope-former, medium-grained, reacts slightly to dilute HCl; 0.25-m-diameter petrified wood 0.4 m above base of unit, oriented N60°E. *2.1*

13. Sandstone, brown on weathered surfaces, red and white mottled on fresh surfaces, well lithified, cliff-former, medium-grained, reacts slightly to dilute HCl; ripple beds and parabolic tabular-planar cross-beds; laminae 1 mm thick, cleaves easily along laminations; contact with underlying unit is erosional; dips 5 degrees, S20°E. *1.0*

12. Mudstone and sandstone. Mudstone, light red on weathered surfaces and brick red on fresh surfaces with green mottles; sand grains present; interpreted to be a C soil horizon (slightly weathered parent material). Sandstone, hematite stained on weathered surfaces, white or gray on fresh surfaces, poorly lithified, fine-grained, well sorted, subangular grains with limited

feldspar and trace amounts of black minerals; indeterminately cross-bedded sets 0.1 m thick, made up of laminations that are 0.3 to 0.5 cm thick; black sand layer, 1-2 cm thick, 0.5 m up from base of unit. *0.8*

11. Mudstone, light green on weathered surfaces, green and red mottled on fresh surfaces, poorly lithified, slope-former, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; contact with lower unit is apparently gradational; interpreted to be a Bt soil horizon with angular blocky peds. *1.0*

10. Mudstone, light red on weathered surfaces with a transition to light orange upward, brick red on fresh surfaces with green mottles, crumbles to 1-mm-diameter angular-blocky structures defined by slickensides, weathers to slope covered in carbonate nodules; contact with underlying unit abrupt; interpreted to be a Bt(c?) soil horizon with angular blocky peds and nodules. *3.6*

9. Mudstone, white to yellow on weathered surfaces, brown on fresh surfaces with red and green mottles, crumbles into 1-mm-diameter angular-blocky to granular structures, weathers to slope

covered in carbonate nodules; interpreted to be a Btc soil horizon with angular blocky peds and nodules. *2.8*

8. Mudstone, light red on weathered surfaces, brick red on fresh surfaces with green mottles, crumbles to 1-mm-diameter angular-blocky structures defined by slickensides, weathers to slope covered in carbonate nodules; contact with underlying unit is gradational, underlying sandstone likely protolith; interpreted to be a Bt(c?) soil horizon with angular blocky peds and possible nodules. *3.1*

7. Sandstone, light red on weathered surfaces, dark red on fresh surfaces, moderately well lithified, some beds more resistant than others, fine- to medium-grained, well sorted with limited feldspar; angular-trough cross-beds 0.1 m thick composed of 1-mm-thick laminations; contact with lower unit gradational. *5.5*

6. Sandstone, lavender on weathered surfaces, alternating beds of white to light green and light purple to red on fresh surfaces; moderately well lithified, slope-former, well sorted, composed of angular to sub angular grains of quartz, feldspar, and green and black minerals, carbonate cemented; very low angle cross-beds,

likely trough cross-bedded; contact with lower unit abrupt; petrified trees present at the top of unit with orientations N12°E, N55°W, N60°E. *1.1*

5. Sandstone and conglomerate. Sandstone, dark brown on weathered surfaces, alternating beds of white and light purple to red on fresh surfaces, resistant, ledge-former; medium-grained, well sorted composed of angular to sub angular grains of quartz, feldspar, and green minerals; cement has a slight reaction to dilute HCl; cross-beds average 0.23 m thick, interbedded with large cross-sets are discontinuous 2-cm-thick sets. Conglomerate, in the base of the channel, well cemented, clasts predominantly red mudstone with some large rip-up clasts of sandstone; vertebrate bones smooth with small, shallow striations covering the surface, inside of the bone porous, highly fragmented; contact with lower unit erosional, channel fill. *0.9*

4. Mudstone, light red on weathered surfaces, purple to red on fresh surfaces with rare green mottles that increase in abundance upward until becoming dominant, poorly lithified, slope-former, crumbles to 2- to 8-mm-diameter angular-blocky structures defined by slickensides; calcite cemented, more resistant layer present;

interpreted to be a Bt soil horizon with angular blocky peds and a K soil horizon within it. *25.7*

3. Mudstone, light green on weathered surfaces, green on fresh surfaces, splotches of yellow form an irregular, non-calcareous layer that is up to 0.1 m thick within the unit, poorly lithified, slope-former, crumbles to 1-mm- to 0.5-cm-diameter angular-blocky structures defined by slickensides; there is 0.15-m-thick interval where structures increase to 2 cm diameter, then size decreases again; interpreted to be a Bt soil horizon with angular blocky peds. *2.0*

2. Mudstone, light red on weathered surfaces, purple to red on fresh surfaces with rare green mottles, grades from purple to red lower down in the unit; in the purple unit, fresh surfaces show dark purple to red soil with green mottles, some sand grains, crumbles to granular structures up to 1 mm diameter defined by slickensides; calcite nodules 1 cm to 0.5 m in diameter, increase in abundance upward, form layer near top of the unit; weathers to a slope covered in mostly fragmented calcite nodules; whole nodules have a botryoidal appearance; evidence of slumping in mudstones;

interpreted to be an Ac soil horizon with granular peds and nodules. *1.5*

1. Mudstone, light red on weathered surfaces, purple to red with green mottles on fresh surfaces, grades from purple to red lower in the unit, some sand grains, crumbles to granular structures up to 1 mm diameter defined by slickensides; calcite nodules 1 cm to 0.5 m diameter increase in abundance upward; weathers to slope covered in mostly fragmented calcite nodules; whole nodules have a botryoidal appearance; interpreted to be an Ac soil horizon with granular peds and nodules. *1.5*

Total of Petrified Forest Member *83.9*

Monitor Butte Member

9. Sandstone, hematite stained on weathered surfaces, lavender on fresh surfaces, resistant, very fine-grained, well sorted, homogeneous, micaceous; black minerals define laminations and cleavage; horizontally laminated and cross-bedded; sinusoidal tabular-planar cross-beds 1 cm thick composed of beds 1 mm thick (may be created by ripples); cross-beds most abundant at top of the unit; cleaves easily along laminations. *0.5*

8. Covered. *2.5*

7. Sandstone, hematite stained on weathered surfaces, light green on fresh surfaces, resistant, very fine-grained, well sorted, homogeneous, micaceous; black minerals define laminations and cleavage; horizontally laminated and cross-bedded, sinusoidal tabular-planar cross-beds 1 cm thick composed of beds 1 mm thick (may be created by ripples); cross-beds most abundant at top of the unit; cleaves easily along laminations. *0.5*

6. Covered. *2.5*

5. Sandstone, green and brown on both weathered and fresh surfaces; very fine-grained; horizontally laminated; laminations grouped into beds up to 1 m thick. *2.0*

4. Covered. *1.5*

3. Sandstone, hematite stained on weathered surfaces, green with red polka dots on fresh surfaces, resistant, forms a prominent ledge traceable laterally over large distances; finely laminated in ripple-

laminations; laminations grouped into beds up to 1 m thick; non-calcareous. *0.5*

2. Mudstone to siltstone, gray green on weathered and fresh surfaces, micaceous, horizontally laminated; laminations grouped into beds up to 1 m in thickness. *2.0*

1. Sandstone, hematite stained on weathered surfaces, light green on fresh surfaces; resistant, fine-grained, well sorted, homogeneous, micaceous, black minerals define laminations and cleavage; symmetrical ripples higher in the section grade downward to 1 mm thick horizontal laminations; base of unit obscured. *0.1*

Total of Incomplete Monitor Butte Member 12.1

Total of Incomplete Chinle Exposure 139.5

<u>Little Bown Bench Stratigraphic Column</u>

Measured 2.65 km east-southeast of the Wolverine Petrified Wood area trailhead, 0.1 km south of the road, on the northernmost slope of Little Bown Bench, traversing to the west 0.5 km up the slope to the western side of the bench. Measurement completed where the northern lobe of the bench meets the main body of the bench, from approximately 37° 47'21" N, 111° 10'54"W to 37° 47'10"N, 111° 11'13"W.

Wingate Formation

1. Sandstone, yellow on weathered and fresh surfaces; well sorted, medium-grained, quartz rich; large-scale cross-beds; contact with underlying member is sharp, but does not appear erosional; resistant, cliff-former.

Top of section, top of formation.

Chinle Formation

Church Rock Member

4. Mudstone, red and green mottled on fresh and weathered surfaces, blocky, poorly lithified, cliff forming, protected by Wingate; contact gradational with underlying unit. *1.0*

3. Sandstone and conglomerate. Sandstone, dark red on weathered and fresh surfaces with rare white lenses, poorly lithified but still cliff-forming because of protection by Wingate, fine-grained; generally massive with limited convoluted bedding. Conglomerate, rare matrix-supported stringers or lenses of white gravel, clasts coarse sand to 7.0 cm diameter, angular, and poorly sorted. *1.0*

2. Mudstone, red and green mottled on fresh and weathered surfaces, blocky, poorly lithified, cliff-forming, protected by Wingate; contact gradational with underlying unit. *1.5*

1. Sandstone, light tan on weathered surfaces, fine-grained, well sorted, porous on weathered surfaces, holes 0.1cm to 0.1 m in diameter, concentration of holes increases upward in the unit. *1.0*

Total of Church Rock Member *4.5*

Owl Rock Member

4. Mudstone, green on weathered surfaces, slope-forming; calcite nodules 1-2 cm in diameter. *6.5*

3. Mudstone, light green and pink mottled on weathered surfaces, pink to brown on fresh surfaces with reddish brown root traces and rare reduction spots, well lithified, crumbles into angular-blocky structures defined by slickensides, does not react to HCl; interpreted to be a Bt soil horizon with angular blocky peds. *1.0*

2. Mudstone, slope-forming, small, nearly columnar structures. *6.0*

1. Mudstone, white to light green on weathered surfaces, well cemented; nodules, silica 1-3 cm diameter, concentrically formed, oblong or joined to form peanut shapes; carbonate cemented; generally massive, top appears fractured and columnar; interpreted to be a Bqk soil horizon, silica enriched and a slight reaction to dilute HCl. *1.2*

Total of Owl Rock Member *14.7*

Petrified Forest Member

30. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, variable resistance, alternates between slope-forming and cliff-forming, crumbles into angular-blocky structures 2 to 10 cm in diameter; interpreted to be a Bt soil horizon with angular blocky peds. *14.0*

29. Siltstone, red on weathered surfaces, red and green mottled on fresh surfaces, bedded in1-mm-thick horizontal laminae; discontinuous. *2.0*

28. Mudstone, light green on weathered surfaces, green with red mottles on fresh surfaces, poorly lithified, slope-former, crumbles to 1-cm-diameter angular-blocky structures defined by

slickensides; discontinuous; interpreted to be a Bt soil horizon with angular blocky peds. *2.4*

27. Mudstone, light red on weathered surfaces, brick red with green mottles on fresh surfaces, poorly lithified, slope-former; some sand grains, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; contact with underlying unit gradational, likely the protolith; interpreted to be a Bt soil horizon with angular blocky peds. *2.4*

26. Sandstone, alternating red and white beds on weathered surfaces, interbedded brown and white beds on fresh surfaces, unlithified; rare interbeds of clayey material. *1.5*

25. Sandstone, black (magnetite). *0.1*

24. Sandstone, alternating red and white beds on weathered surfaces, interbedded brown and white beds on fresh surfaces, unlithified; rare interbeds of clayey material. *3.5*

23. Sandstone, light yellow on weathered surfaces, brown on fresh surfaces, massively bedded, unlithified; rare interbeds of clayey material.

22. Sandstone, alternating red and white beds on weathered surfaces, interbedded brown and white beds on fresh surfaces, unlithified; rare interbeds of clayey material.

21. Sandstone, alternating red and white beds on weathered surfaces, interbedded brown and white beds on fresh surfaces, unlithified; rare interbeds of clayey material; petrified wood present; contact with underlying unit gradational.

20. Conglomerate, yellow on weathered and fresh surfaces; clasts poorly sorted, angular to rounded, low sphericity, up to 2.3 cm diameter, predominantly rip-ups from underlying layers with a limited amount of carbonate, matrix-supported; matrix medium-grained sandstone, fines upwards, silica-cemented; cement is white to light turquoise green; indeterminately cross-bedded; rare lenses of finer (less than a cm to coarse sand) clasts within the conglomerate; contact with underlying unit erosional.

10. Mudstone, white to yellow on weathered surfaces, brown on fresh surfaces with reduction spots, resistant, breaks irregularly into angular pieces; interpreted to be a C soil horizon with slightly weathered parent material. *2.0*

9. Mudstone, light red on weathered surfaces, brick red on fresh surfaces, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; contact with underlying unit gradational, likely the protolith; interpreted to be a Bt soil horizon with angular blocky peds. *3.6*

8. Chert, aqua green on fresh surfaces, does not react to dilute HCl; interpreted to be a silica-enriched Bq soil horizon. *0.1*

7. Mudstone, light red on weathered surfaces, brick red on fresh surfaces, crumbles to 1-cm-diameter angular-blocky structures defined by slickensides; contact with underlying unit is gradational, likely the protolith; interpreted to be a Bt soil horizon with angular blocky peds. *3.0*

6. Sandstone, hematite stained on weathered surfaces, alternates red and white with some yellow beds on fresh surfaces, moderately well lithified, slope-former; moderately sorted, medium-grained, composed of angular to subangular grains with limited feldspar and trace amounts of muscovite, biotite, and green mineral, limited carbonate in cement (reacts weakly to dilute HCl); beds 0.1 to 0.2 cm thick, 7-cm-thick angular planar cross-beds; magnetite gives definition to cross-beds; interbedded with the sandstone are 5-cm-thick clayey beds; 0.5- to 2-cm-thick veins of sparry calcite cut through unit, have stacked or layered appearance; contact with underlying unit gradational. *2.5*

5. Sandstone, white and lavender on weathered surfaces, moderately well lithified, moderately sorted, medium-grained, composed of angular to subangular grains with limited feldspar and trace amounts of muscovite, biotite, and green mineral, some carbonate present; parabolic, trough cross-beds indicate a flow direction of S70°W, beds dip 12°SW; contact with underlying unit either erosional (channel fill) or gradational. *2.1*

4. Conglomerate, gray on weathered surfaces; clasts angular, predominantly non-fissile shale, limited calcite, and sandstone,

maximum 5 cm diameter; sandstone matrix similar to underlying unit except higher black mineral content; calcite-cemented, clast-supported; indeterminate structure; discontinuous; channel fill contact with underlying unit erosional. *0.1*

3. Sandstone, lavender with 1- to 2-cm-diameter reduction spots on weathered surfaces, moderately well lithified, slope-former, moderately sorted, medium-grained, composed of angular to subangular clasts with limited feldspar and trace amounts of muscovite, biotite, and a green mineral, carbonate present in matrix, indeterminate cross-bedding. *0.9*

2. Mudstone, red on weathered surfaces, red on fresh surfaces, no visible mottles; yellow carbonate nodules 1 to 4 cm diameter, maximum 0.2 by 0.05 by 0.2 m, arranged in layers; crumbles to angular-blocky structures defined by slickensides; interpreted to be a Btc soil horizon with angular blocky peds and nodules. *22.0*

1. Mudstone, grayish green on weathered surfaces, green with red mottles on fresh surfaces; 1- to 4-cm-diameter yellow carbonate nodules; crumbles to angular-blocky structures; interpreted to be a Btc soil horizon with angular-blocky peds and nodules. *4.0*

Total of Petrified Forest Member *78.6*

Bluewater Creek Member

3. Sandstone, dark brown on weathered surfaces, resistant, fine-grained, calcite-cemented (possible limestone); bedded in 1-mm-thick wavy beds; discontinuous. *0.5*

2. Mudstone, grayish green on weathered surfaces, mottled green and red on fresh surfaces; 1- to 3-cm-diameter yellow carbonate nodules; some fine-grained sandstone; some relict bedding; interpreted to be a Cc soil horizon, slightly weathered parent material with nodules. *5.0*

1. Mudstone, purple to red on weathered surfaces, mottled green and red on fresh surfaces; 1-cm-diameter yellow carbonate nodules, fine sand grains present; interpreted to be a Cc soil horizon, slightly weathered parent material with nodules. *7.2*

Total of Bluewater Creek Member *12.7*

Monitor Butte Member

1. Sandstone, resistant, fine-grained, quartz-rich, bedded in a series of 0.1-m-thick lenses and layers with thin, discontinuous layers of

coarse-grained sandstone interbedded; evidence of slumping and/or faulting during deposition; contact with underlying unit erosional; 13.0 m above base, well lithified 0.2-m-thick sandstone layer; 10.5 m above base carbonized log; 6.0 to 10.0 m above base covered; 3.8 to 6.0 m above base, medium- to coarse-grained, quartz-rich, cross-bedded sandstone with moderately rounded grains; 3.3 m above base, highly carbonaceous layer containing many fragments of wood. *14.0*

Total of Monitor Butte Member *14.0*

Shinarump Member

5. Sandstone and siltstone. Sandstone, medium-grained, moderately to well sorted, grains sub-angular, predominantly quartz, approximately 5% black minerals; 0.6-m-thick angular cross-beds; fills channels cut into underlying unit; very rich in petrified wood. Siltstone, quartz-rich; contact with underlying unit erosional, channel fill; carbonized trees abundant, associated with yellow siltstone, crop out in layers exhibiting preferential orientation, N38°W, N32°W, N15°W, N32°W. *3.7*

4. Siltstone and sandstone. Siltstone, gray on fresh surfaces; micaceous. Sandstone, fine-grained, quartz-rich, inclusions of

siltstone 2-3 cm in diameter and medium-grained sandstone up to a m in length, similar to underlying sandstone; fragments of carbonized wood up to 0.2 m across. *0.9*

3. Sandstone, resistant, medium-grained, well sorted, clasts primarily rip-ups of well sorted, fine-grained sandstone, 0.12 x 0.05 m in size, original bedding preserved; fining downward, degree of rounding decreases downward; contact with underlying unit erosional, fills channels. *0.2*

2. Conglomerate, composed of clasts of rounded quartz, red chert, and black chert, angular white-gray shale, average 1 cm diameter, maximum 3 cm diameter; contact with lower unit erosional, fills channel. *0.1*

1. Sandstone, hematite stained on weathered surfaces, yellowish brown on fresh surfaces, medium- to coarse-grained, less than 1% larger inclusions and clasts; clasts angular, predominantly quartz; white, opaque, non-calcareous cement; 0.1-m-thick angular tabular-planar cross-beds; porous. *0.3*

Total of Incomplete Shinarump Member *5.2*

Total of Incomplete Chinle Exposure *129.7*

Base of section covered

Moenkopi Formation

1. Mudstone, brick-red, horizontally bedded.