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Sedimentology of the Upper Triassic Chinle Formation Southeastern Utah: Paleoclimatic Implications

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SEDIMENTOLOGY OF THE UPPER TRIASSIC CHINLE FORMATION, SOUTHEASTERN UTAH: PALEOCLIMATIC IMPLICATIONS

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ABSTRACT

The Upper Triassic Chinle Formation in southeastern Utah was deposited in a complex fluvial-deltaic-lacustrine system. The Chinle records the evolution of a continental system in response to variations in climate, tectonics, and sediment supply. Chinle strata represent deposits of fluvial channels and floodplains; lacustrine deltas; lacustrine basins; and lacustrine and playa mudflats. These rocks include a variety of vertebrate, invertebrate, and plant fossils, trace fossils, and paleosols that provide information on depositional environments, water tables, and paleoclimate.

Sedimentologic and paleontologic interpretations both support an interpretation of abundant lakes, streams, and marshes with high, but fluctuating water tables for all but the last phase of Chinle deposition. This final phase represents a transition to eolian deposition of the Wingate erg. The Chinle climate is interpreted to have been characterised by tropical monsoons, with abundant precipitation and seasonally drier periods. This interpretation agrees with Late Triassic paleoclimates predicted from theoretical models.

INTRODUCTION

In southeastern Utah, erosion by the Colorado River and its tributaries has produced extensive three-dimensional exposures of the Upper Triassic Chinle Formation. Sedimentological examination of the Chinle Formation through measured stratigraphic sections (Figure 1) and reconstruction of stratigraphic cross-sections has enabled an interpretation of its complex continental depositional environments. These interpretations are based on sedimentary structures, lithofacies variability of process-controlled genetic units, and paleosol horizons. The resulting depositional model provides a depositional framework for the formation that accounts for the observed lithofacies variation, and depicts the paleogeography at the time of deposition. The sedimentologic investigation incorporates observations of the fauna, flora, and trace fossil assemblages. While many of these fossils are not age diagnostic, the assemblages and their mode of formation impose restrictions on the model. The model, in turn, provides valuable information for the interpretation of the Late Triassic paleoclimate.

Several publications in recent years have addressed various aspects of the stratigraphy and depositional environments of the Chinle Formation. An inclusive review of previous investigations of the Chinle Formation on the Colorado Plateau and interpretations of the stratigraphy, depositional environments, fossils, and paleoclimate of the Chinle is provided by Stewart et al. (1972a). Stewart et al. (1972b) contains a summary of Chinle nomenclature development. Lupe (1977, 1979, 1984) investigated Chinle depositional environments in the San Rafael Swell, Utah and in the vicinity of Moab, Utah. Gubitosa (1981) and Blakey and Gubitosa (1983, 1984) interpreted depositional environments and fluvial architecture of the Chinle, based primarily on detailed work in Canyonlands National Park, Utah and in Arizona. Working with extensive three-dimensional exposures in southeastern Utah, Dubiel (1982, 1983a, 1983b, 1984, 1985, 1986) developed a detailed depositional model for Chinle environments depicting a complex fluvial-deltaic-lacustrine sequence in southeastern Utah. Kraus and Middleton (1987) investigated the sedimentology of the Chinle Formation in Petrified Forest National Park, Arizona. Dubiel et al. (1987) discussed the occurrence of lungfish burrows in the Chinle and related Dolores Formation.

While there is a general concensus on the interpretation of continental depositional environments and the depositional history of the Chinle Formation, there is a corresponding lack of agreement regarding the interpretation of the climate during Chinle deposition. Climatic interpretations, based on a variety of stratigraphic and paleontologic evidence, range from arid and semi-arid conditions (Stewart et al. 1972a; Lupe 1979) with through-flowing streams (Daugherty 1941) to a humid tropical climate (Ash 1967, 1972, 1978; Gottesfeld 1972) or a humid climate with increasing aridity with time (Blakey and Gubitosa 1983). Recent sedimentological studies (Bown et

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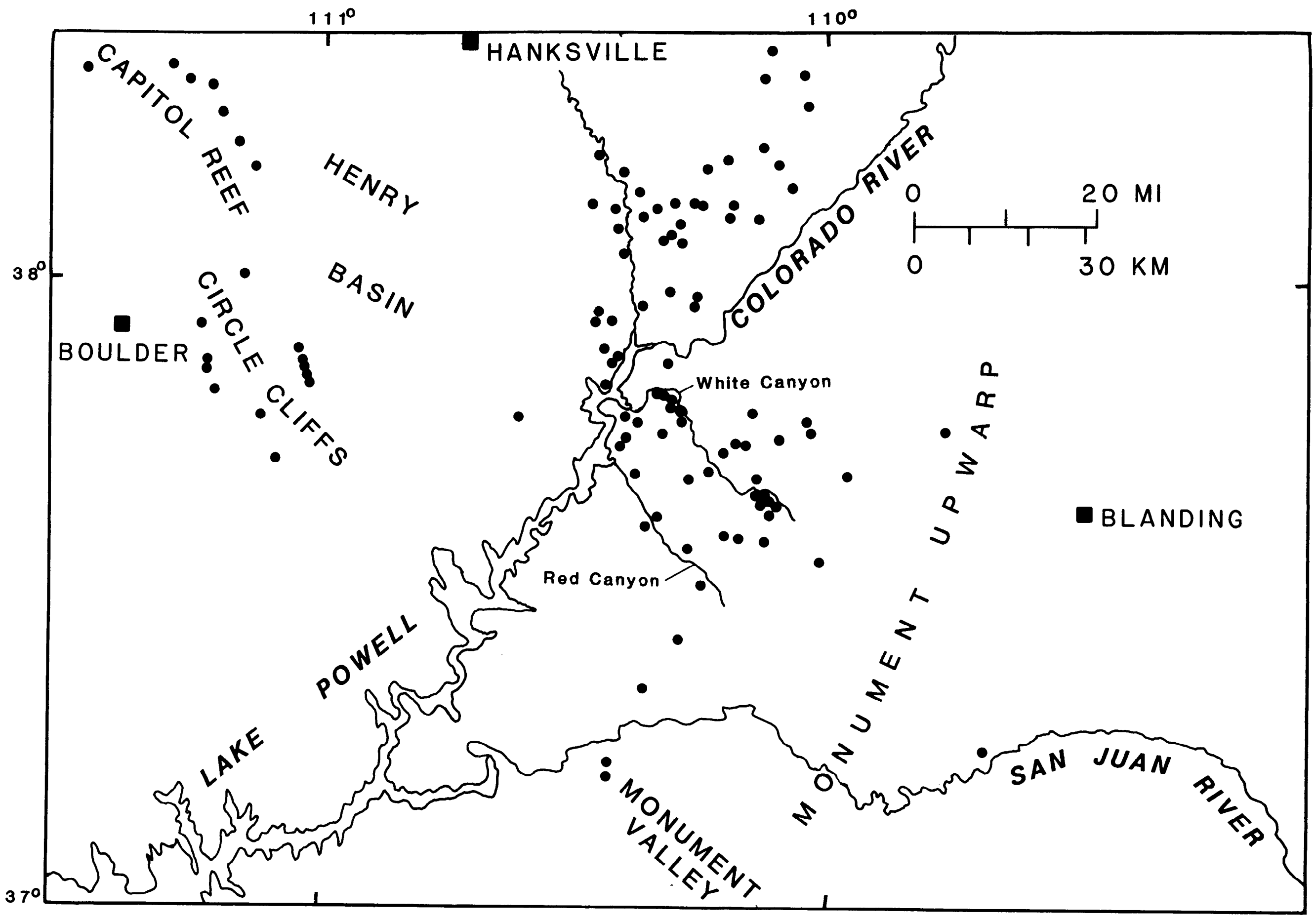

Figure 1. Map showing location of measured sections and geographic features referred to in the text.

al. 1983) in Petrified Forest National Park, Arizona and in southeastern Utah (Dubiel 1983b, 1984, 1986) have characterized the climate as being wet but punctuated by seasonally dry periods. In addition, the identification of lungfish burrows and superimposed gley paleosols in the Chinle and Dolores Formations (Dubiel et al. 1987) supports these interpretations of a tropical monsoonal climate. Paleoclimatic models (Robinson 1971; Parrish et al. 1986) also indicate a tropical monsoonal climate for the Late Triassic.

Sedimentological study of the Chinle Formation in southeastern Utah has provided a variety of evidence that bears on the interpretation of paleoclimate during the Late Triassic. The Chinle depositional model depicts a complex fluvial-deltaic-lacustrine system replete with extensive marshes, bogs, floodplains, and mudflats. The presence of these environments indicates that water was abundant in the depositional system. Paleosols developed on subaerial and seasonally flooded portions of the floodplains and lake margins indicate that groundwater levels fluctuated in response to periodic flooding.

Trace fossils that have been interpreted as the casts of lungfish burrows (Dubiel et al. 1987) are found in various lithofacies of all members of the Chinle. The ubiquitous lungfish burrows and the recent discovery of lungfish teeth in Utah (Dubiel 1987; Parrish and Good 1987) indicate that lungfish were abundant in the Chinle ecosystem. This abundance of lungfish indicates that the climate provided sufficient moisture to form extensive lakes, streams, and marshes for lungfish habitats. The occurrence of aquatic vertebrates such as phytosaurs and metoposaurs (Parrish and Good 1987) supports the previous interpretations of humid climatic conditions with extensive lakes, streams, and marshes. The recent discovery of unionid bivalves in the Chinle of Utah provides additional evidence for both lacustrine and perennial fluvial conditions (Parrish and Good 1987; Good et al. 1987).

Paleomagnetic studies indicate that the major lucus of Chinle deposition was about 0° to 20° north latitude (Van der Voo 1976), that is, clearly within the tropics. Thus, the sedimentologic and paleontologic evidence are complimentary (Good et al. 1987) and indicate that tropical monsoons with abundant precipitation and seasonally dry spells characterized the climate during Chinle deposition.

REGIONAL STRATIGRAPHY

The Chinle Formation in southeastern Utah consists of six formal members (Stewart et al. 1972a): the Shinarump,

Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock Members, in ascending order. In the study area, the Chinle Formation unconformably overlies the Lower and Middle (?) Triassic Moenkopi Formation. The Chinle Formation is overlain by the Upper Triassic Wingate Sandstone.

Generally, the Chinle Formation fills large paleovalleys incised into the Moenkopi Formation (Stewart et al. 1972a; Blakey 1974; Blakey and Gubitosa 1983; Dubiel 1983b, 1986); these paleovalleys formed in response to a lowered regional baselevel. A subsequent rise in baselevel resulted in aggradation and the filling of the paleovalleys by the continental Chinle sediments. Specific lithofacies, their distribution within the various members, and their interpreted depositional environments are discussed in the following sections.

SEDIMENTOLOGIC EVIDENCE FOR WET ENVIRONMENTS

The members of the Chinle Formation were deposited in a complex fluvial-deltaic-lacustrine system (Blakey and Gubitosa 1983; Dubiel 1983b, 1984, 1985, 1987). Consequently, the lithofacies include a complex array of lithologies and sedimentary structures indicative of the environment of deposition. The lithofacies and sedimentologic and climatic interpretations for each member of the Chinle are discussed in the following sections.

Lithofacies and Depositional Environments

The Shinarump Member is characterized by white to yellow and gray, medium- to coarse-grained and conglomeratic sandstone. The sandstone is cut by complex cut-and-fill structures, lenticular internal scour surfaces, and large-scale lateral accretion bedding. Abundant, large-scale, trough cross-stratification and less abundant tabular planar cross-stratification and horizontal laminations are common sedimentary structures. Sandstone bodies grade laterally into siltstone and mudstone lenses that contain organic-carbon fragments and whole, carbonized plant fossils.

Lithology, sedimentary structures, and isopach maps (Dubiel 1983b) indicate that the Shinarump Member represents fluvial strata deposited under conditions of rising baselevel in the lowest portions of the paleovalleys cut into the Moenkopi Formation (Figure 2). The transition from massive, conglomeratic, and tabular-planar stratified sandstone at the base upward into medium-grained, trough cross-stratified sandstone is thought to represent a change from essentially bedload deposition in braided streams with transverse bars to mixed-load deposition in more sinuous fluvial systems with sand waves and point bars.

In the Circle Cliffs and near Capitol Reef (Figure 1), the fluvial sandstones of the Shinarump Member have been cut out by large-scale scours or paleovalleys that have subsequently been filled by green Monitor Butte Member strata. These scours are interpreted to represent cuts into and removal of portions of the Shinarump in response to locally lowered baselevel, possibly due to lake-level fluctuations. Similar cuts and fills have been reported from the Petrified Forest Member in Arizona (Kraus and Middleton 1987).

Figure 2. Shinarump Member of the Chinle Formation at Colt Mesa in the Circle Cliffs, Utah. Shinarump fluvial conglomerate and sandstone fill a large paleovalley cut into the underlying Moenkopi Formation. Slope of paleovalley wall cut into Moenkopi is visible at arrow. Mine adits are 3 m high.

Where these cuts are not present, a gradational contact exists between the Shinarump Member and the overlying Monitor Butte Member, which may be the most heterogeneous lithologic unit in the Chinle Formation. The Monitor Butte contains purple-mottled, yellow to brown, and red sandstones and siltstones; green, bentonitic, silty sandstones and mudstones; red, calcareous mudstone; black, organic-carbon-rich mudstones; and pink and green to tan limestones. Because of the complex interfingering and lateral variability of these lithofacies and the diverse depositional environments that they represent, each will be discussed in more detail, beginning with the basal units and working up through the section.

Directly overlying the Shinarump Member, but often exhibiting a gradational contact with the rocks below, is a purple-, yellow-, and white-mottled sandy siltstone and sandstone interval referred to here as the purple-mottled unit (PMU) of the Monitor Butte. The PMU is generally silicified and is characterized by large, irregularly shaped color mottles of dark purple, lavender, yellow, and white. The variations in color are the result of varying concentrations of iron-bearing minerals. Dense concentrations of hematite occur in the dark purple areas, there is less hematite in the lavender areas, a hydrated iron compound (probably limonite) colors the yellow areas, and hematite

is absent in the white areas. Ubiquitous in the PMU are large cylindrical trace fossils (Figure 3) interpreted to be the casts of lungfish burrows (Figure 4) (Dubiel et al. 1987).

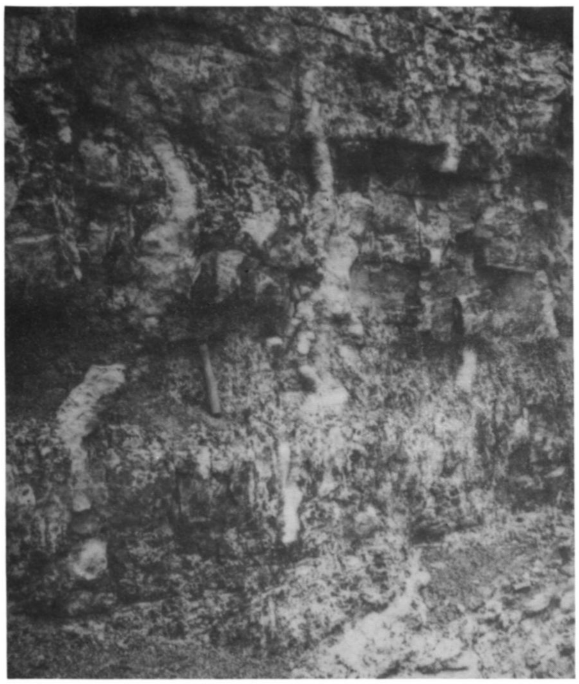

Figure 3. Purple and white-mottled unit of the Monitor Butte Member with distinctive white tubular trace fossils interpreted to be lungfish burrows. Hammer for scale.

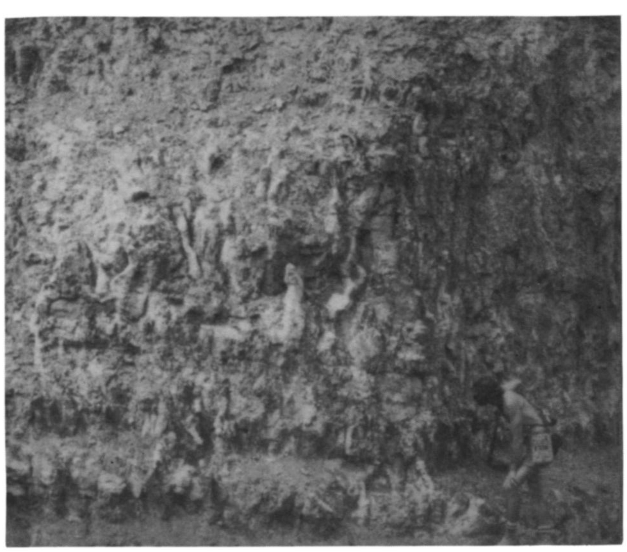

Figure 4. Purple and white-mottled siltstones and sandstones of the Monitor Butte Member with very abundant lungfish burrows.

Both the lungfish burrows and the mottled coloration of these rocks are thought to reflect fluctuating water tables within the sediments, probably in response to seasonal flooding (Dubiel et al. 1987). The lungfish are believed to have formed the burrows for aestivation in response to seasonal dryness. Fluctuating water tables that produced alternating oxidizing and reducing conditions resulted in redistribution of iron within the sediments. As organic matter in the sediment was oxidized, iron was reduced. The iron was then mobilized in the reduced state, and reprecipitated under oxidizing conditions that developed during subsequent drying. The purple and white mottling extends laterally into the Moenkopi (Figure 5) at the same level of development in the Chinle and, in both cases, represents a gleyed paleosol formed in response to fluctuating water tables.

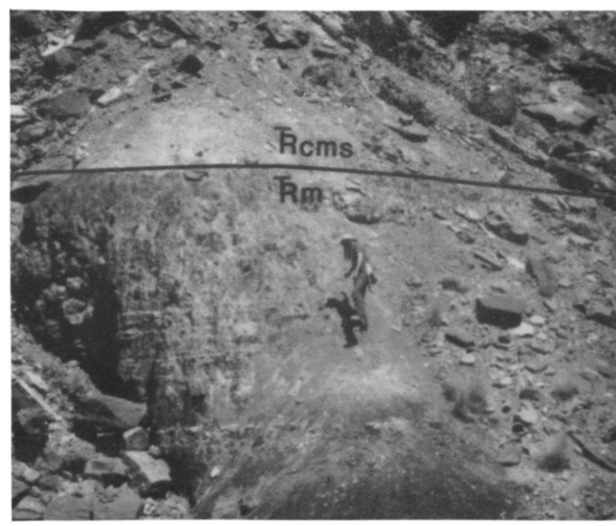

Figure 5. Purple and white-mottled paleosol formed on the Moenkopi (TR m) and overlain by Chinle mudstones of the Monitor Butte Member (TR cms). Note the decreasing intensity of the pedogenic alteration with increasing depth in the Moenkopi.

The sandy siltstone and sandstone facies of the PMU can generally be traced laterally into gray and purple siltstones that contain finely comminuted fragments of plant material and organic-carbon fragments. The siltstones can further be traced laterally and distally into black, very thinly and horizontally laminated, organic-carbon-rich mudstones. The black mudstones typically contain abundant, chitinous tests of conchostracans, fish scales, and fragmented fish bones; whereas gray mudstones that have a lower organic-carbon content contain abundant, calcareous *Darwinula* ostracodes and organic-carbon fragments (Dubiel 1983b). The black mudstones are as much as 15 m thick and in places contain lenses of coal as much as 20 cm thick. Locally, the mudstones grade into purple-mottled gray mudstones and tan thin-bedded limestones that contain ostracodes, thin-shelled unionid bivalves, and

small vertebrate bones (Dubiel 1987; Parrish and Good 1987).

These Monitor Butte units represent coarse-grained clastic deposition in fluvial systems and related fine-grained clastic and organic-carbon deposition in overbank and lacustrine-marsh and bog wetland environments (Dubiel 1984). Alternation of conchostracan- and ostracode-rich horizons within mudstone units indicates that water levels in the lakes and marshes must have fluctuated somewhat, causing small-scale transgressions and regressions of the laterally adjacent environments (Dubiel 1984). Conchostracans typically inhabit ephemeral pools and lacustrine marshes that are subjected to seasonal drying, while *Darwinula* sp. ostracodes are indicative of a more permanent lacustrine environment (R. M. Forester, written comm. 1982; Dubiel 1983b). The occurrence of these particular conchostracans and ostracodes within the same mudstone beds suggests that the water chemistry may be characterized by a slightly alkaline pH of 7.5 to 8 and that the salinity of the water was less than 5 parts per thousand (R. M. Forester, written comm. 1982; Dubiel 1983b). The freshwater salinity is supported by the analysis of organic-carbon content of as much as 20 weight percent in the mudstones and the occurrence of coal, which necessitates a continually high, fresh water table in a continental setting to preserve organic material. The thin-bedded fossil-bearing carbonates and mudstones represent deposition in small lacustrine systems.

Gradationally overlying the PMU and related marsh and lacustrine units are a series of laterally extensive but thin-bedded, burrowed limestones and *Darwinula* ostracode-bearing mudstones as much as 5 m thick. These, in turn, are overlain by a sequence of green, bentonitic, sandstones, siltstones, and sandy mudstones that commonly exhibit large-scale foreset bedding as much as 25 m thick (Figure 6) (Dubiel 1983b). The foreset beds internally consist of abundant climbing, lunate ripples capped by thin, 2 cm-thick zones of oscillation ripples. The green beds invariably contain well-preserved finely comminuted black, organic plant fragments and whole specimens of several Late Triassic plants, including true ferns (Figure 7) (Ash et al. 1982) and the casts of giant horsetails (*Equisetities* sp.) (Figure 8) (Holt 1947; Ash 1967, 1972) as much as 20 cm in diameter.

Based on lithology, sequence of deposition, paleocurrent measurements, and isopach maps, these beds have been interpreted as an extensive system of fluvial and deltaic distributary channels and splays, and lacustrine, prodelta, and deltaic deposits (Dubiel 1983b, 1985). The fluvial and deltaic systems prograded northwest into a large lake, filling in most of the remnant topography of the original Moenkopi paleovalleys. The bentonitic character of these Monitor Butte rocks and the presence of altered lithic clasts (Schultz 1963) and relict glass shards (Waters and Granger 1953) indicate that volcanic ash was a major component of the sediment.

Figure 6. Foreset beds of a lacustrine Gilbert-type delta in the Monitor Butte Member near Lake Powell, Utah. Geologist (arrow) for scale.

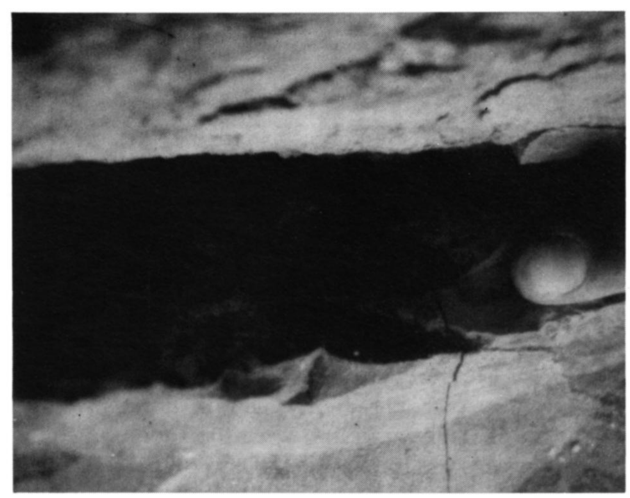

Figure 7. Carbonized plant fossil (the fern *Phlebopteris smithii*) in Monitor Butte deltaic beds in White Canyon.

The Moss Back Member occurs in a narrow outcrop belt between White Canyon, Utah and Canyonlands National Park, Utah (Blakey and Gubitosa 1983; Dubiel 1983b). The Moss Back consists of brown to gray, medium-grained sandstone and carbonate-nodule conglomerate with minor mudstone lenses. Sedimentary structures include abundant tabular planar and large-scale trough crossbedding with less abundant horizontal lamination. The sandstone bodies are lenticular and exhibit internal scour surfaces and cut-and-fill structure. Generally, the Moss Back erosively overlies the Monitor Butte, but in White Canyon it exhibits some important lateral relationships with the Monitor Butte. The thick tabular planar- and trough-crossbedded sandstones interfinger with and grade laterally into red, thin-bedded sandstones, siltstones, and mudstones that contain trans-

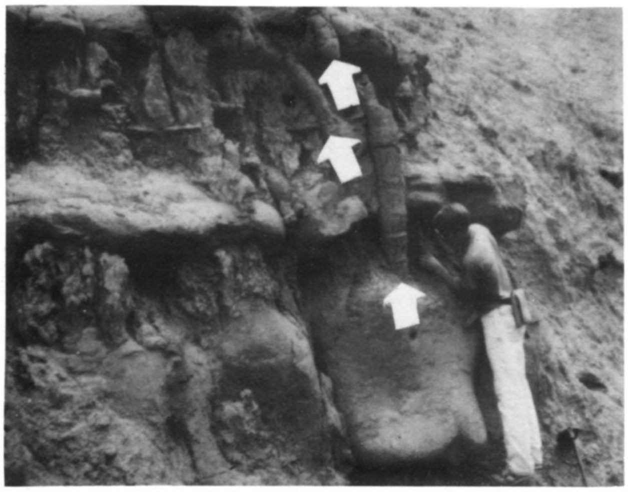

Figure 8. Pith casts of giant horsetails (arrows) in the Monitor Butte Member in Capitol Reef National Park, Utah. The casts were formed when the hollow trunks of the horsetails were broken off and filled with sediment during a flood event.

ported, thick-shelled unionid bivalves (Dubiel 1987; Parrish and Good 1987), isolated carbonate nodules, and abundant, 1 cm-diameter trace fossils with a distinctive external, ropey texture.

This assemblage of lithology and structures in the Moss Back sandstone indicates depostion by fluvial processes. The lenticular, coarse-grained deposits represent deposition in sinuous fluvial channels. The red, thin-bedded units are interpreted as levee, crevasse splay, and overbank deposits that exhibit carbonate-rich paleosol horizons. These paleosols, probably vertisols, were the source of the carbonate nodules within the Moss Back conglomerates. The thick-shelled unionids were washed out of a perennial fluvial system during flood events (Parrish and Good 1987).

The interfingered lateral relationship of these fluvial and floodplain units, and the fact that they overlie and also appear to grade distally into the deltaic units of the Monitor Butte, indicate that at least the White Canyon portion of the Moss Back was the distributary fluvial system to the Monitor Butte deltaic system. The exact relationship of this Moss Back to the Moss Back of Canyonlands National Park to the north and to the overlying Petrified Forest Member in both areas is under investigation.

Overlying the Moss Back are the lavender and brown sandstones and variegated mudstones of the Petrified Forest Member. The bentonitic sandstones and thin lenses of carbonate-nodule conglomerate typically exhibit large-scale trough cross-stratification, larger-scale internal scour surfaces, and lateral accretion bedding. The sandy portions of the units can be traced laterally into red-brown mudstones that contain pedogenic carbonate nodules identical to those in the Moss Back floodplain paleosols. The mudstones contain rare lungfish burrows that are difficult to discern due to their infilling by clastic material identical in size to the surrounding matrix (Dubiel et al. 1987). Interfingered with the sandstones and mudstones are bentonitic sandstone and siltstone strata that contain abundant vertebrate remains, lungfish toothplates, gastropods, and thin-shelled unionid bivalves (Dubiel 1987). Isolated outcrops of black, organic-carbon-rich and conchostracan-bearing mudstone are present in the Petrified Forest Member.

These strata are interpreted to represent fluvial sandstones and floodplain mudstones interfingered with fossil-bearing splay deposits and laterally restricted marsh mudstones. The abundance of lateral accretion bedding, numerous splay deposits, and the presence of floodplain mudstones that completely encase the sandstone units suggest the strata were deposited by sinuous streams that were subject to numerous avulsion events. The remains of aquatic phytosaurs, lungfish, and lacustrine unionid bivalves (Parrish and Good 1987) support the interpretations of rivers, lakes, and marshes for the Petrified Forest strata. Observations of apparent altered glass shards (Waters and Granger 1953) and bentonitic mudstones (Schultz 1963) in the Petrified Forest Member indicate that volcanic ash continued to form a significant component of the clastic input.

The Petrified Forest Member interfingers with and grades upward into the pink and green limestones and red to orange siltstones of the Owl Rock Member. The limestones vary from 10 cm to 2 m thick, can be traced laterally for several miles, and typically display a mottled coloration and knobby-weathered texture. The cylindrical trace fossils interpreted to be lungfish burrows (Dubiel et al. 1987) are locally abundant in the limestones. These burrows often extend down into the adjacent siltstones and are probably responsible for the extensive bioturbation and knobby texture of the rocks. Locally the limestones contain ostracodes, but no other body fossils have been observed. The siltstones are massive, exhibit no sedimentary structures, but locally do contain lungfish burrows and other small trace fossils.

The presence of extensive carbonate units in a continental setting and the occurrence of lungfish burrows in both the limestones and siltstones indicate that deposition occurred in lacustrine basins and on lacustrine margins, respectively. Both the carbonate and the fine-grained clastic deposition imply that significant clastic detritus was not supplied to these environments.

Interfingered with and generally overlying the Owl Rock Member are the orange to red and brown sandstones and siltstones of the Church Rock Member. The Church Rock has a rather limited distribution (Stewart et al. 1972a) and is not present at every locality in the study area. Sandstones are fine- to medium-grained and are either structureless or contain faint, large-scale trough cross-stratification and minor lateral accretion bedding. Many of the units contain small but abundant, meniscate back-filled trace fossils. Mudstones locally contain dessication cracks as much as

10 cm across and up to 1 m deep that are filled with sandstone of the overlying Wingate Sandstone.

These sandstones and mudstones are interpreted to have been deposited on lacustrine or playa mudflats crossed by small fluvial systems with laterally restricted floodplains. The large-scale cross-stratification indicative of eolian deposition and the mudcracks indicate that dessication was more prominent during deposition of the upper part of this member. These environments may, in fact, reflect the progradation of and transition to eolian erg deposition of the overlying Wingate Sandstone. The generally redder coloration of these rocks compared to the variegated colors of the lower Chinle is due to a greater development of diagenetic hematite. The increased development of hematite in this part of the Chinle section is thought to be related to the lack of organic carbon in the rocks. Both hematite development and lack of organic carbon are thought to reflect deposition in the more oxygenated lacustrine mudflat and playa environments. The red coloration by itself is not a direct indicator of arid environments, but merely reflects the increased hematite content.

Depositional Model

The model for Chinle deposition (Figure 9) depicts the complex fluvial-lacustrine system. Shinarump fluvial deposition, which initially filled the lowest portions of the paleovalleys incised into the Moenkopi, progressed upvalley in response to rising baselevel. As headward deposition proceeded up the paleovalleys, erosion was continuing in the headwaters of the drainage basin. The PMU and associated wetlands environments represent deposition at or near the level of the water table, a water table that was progressively rising and drowning the fluvial systems. The water table rise caused the expansion of the lacustrine system that lay to the west. Seasonal flooding of fluvial and floodplain systems, probably related to seasonal precipitation, is indicated by the ubiquitous lungfish burrows and the gleyed paleosols. Thin lacustrine carbonates and mudstones were deposited as the water table rose high enough to form the lake. The area was inhabited by aquatic vertebrates, lacustrine molluscs, and lacustrine microinvertebrates.

An increase in the rate of sedimentation, associated with an increase in volcanic activity and ash production, resulted in the progradation of the Monitor Butte and Moss Back systems. The Monitor Butte represents deposits of Gilbert-type deltas, distributary mouth bars, distributary channels, subaqueous and subaerial levees, and splays of a high-constructional lacustrine delta (Dubiel 1983b). Rapid sedimentation due to seasonal influx of runoff and clastic and volcanic sediment resulted in overloading and deformation on portions of the delta front (Dubiel 1985). Ferns and giant horsetails flourished in the lower delta plain environment, and were buried by rapid sedimentation during flood events. As the system continued to prograde, sediment was deposited in the fluvial channels, splays, floodplains, and mudflats of the Moss Back delta plain. At this time, the pre-Shinarump paleovalleys were essentially filled with sediment, producing a flat depositional plain. Moss Back fluvial systems were inhabited by fluvial unionids that indicate the streams were perennial.

The ash-laden Petrified Forest sinuous fluvial channels, splays, and floodplains prograded over the area. The presence of terrestrial vertebrate remains indicates that

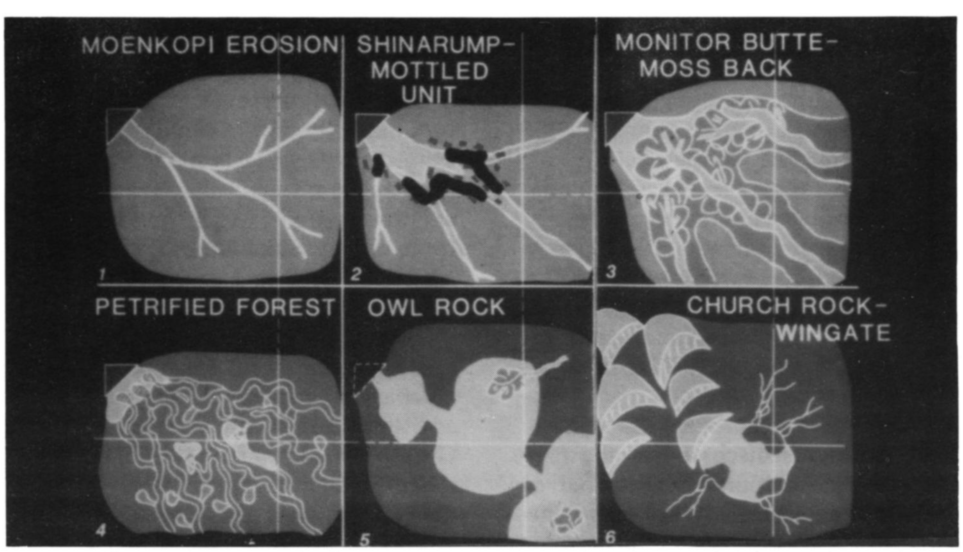

Figure 9. Model showing schematic depositional environments and history of deposition for the Chinle Formation. See text for detailed explanation of the model. Thin white crosshairs in each panel denote the Four Corners area.

terrestrial habitats existed (Parrish and Good 1987), but water table continued to be high, as evidenced by the presence of aquatic vertebrates, lacustrine unionids, and organic-carbon-rich marshes. Owl Rock carbonates, silt, and mud were deposited in an extensive lacustrine environment that developed in response to continued subsidence and to a reduction in clastic and volcanic sediment input. The persistence of lungfish into the Petrified Forest and Owl Rock ecosystems indicates that the climate was still sufficiently wet to form lakes, streams, and marshes. However, the development of isolated carbonate nodules in Petrified Forest paleosols suggests that precipitation was seasonal. The alternation of siltstone and limestone beds in the Owl Rock indicates that there were longer-term fluctuations in the supply of water to the lake.

It is possible that the lacustrine basin was closed during Owl Rock time, and that closure was accomplished by progradation of the Wingate erg from the northwest. Gradually, lower water table conditions developed and playa mudflat siltstones and mudstones and ephemeral fluvial channel sandstones of the Church Rock Member were deposited under more oxygenated conditions that probably represent extended drier periods, although there were certainly intermittent flood events. The inception of playa mudflat deposition and the presence of dessication cracks within these deposits indicate that the environment had to be periodically wet. The overlying deposits of the eolian Wingate erg attest to the transition to more arid climatic conditions.

PALEOCLIMATE

Several lines of sedimentologic evidence discussed in the preceeding sections bear on the interpretation of climate at the time of Chinle deposition. This evidence includes the lithofacies variation and the interpretation of depositional environments into a depositional model; the vertical succession of depositional environments as a reflection of fluctuating water tables; the occurrence of lungfish burrows in gleyed paleosols in several depositional environments and lungfish distribution throughout the Chinle stratigraphic section; the distribution and character of faunal assemblages and trace fossils; paleosols developed on fluvial, floodplain, and exposed mudflat deposits as an indication of frequency and abundance of precipitation; the variation in organic-carbon content and associated color of the rocks as a reflection of water table at the time of deposition; and considerations based on the paleontology of vertebrates, invertebrates, and plants.

The vertical succession of lithofacies and their interpreted depositional environments discussed in the preceeding sections provides a depositional model characterized by fluvial, deltaic, and lacustrine systems. The progression from fluvial Shinarump to marsh, lacustrine, and deltaic Monitor Butte and fluvial Moss Back systems points to the development by expansion and the subsequent infilling of a large lake. The overlying succession from fluvial, floodplain, and marsh Petrified Forest deposits to lacustrine Owl Rock and then playa Church Rock and eolian Wingate deposits indicates the development of another large lacustrine system and its subsequent demise. Factors controlling these large-scale trends include rate and locus of tectonic subsidence, rate of sediment supply from tectonic and volcanic sources, and amount and seasonal distribution of precipitation as a reflection of long-term climate.

Smaller-scale variations within lithofacies, such as the numerous climbing ripple and oscillation ripple sequences in the Monitor Butte (Dubiel 1983b), variations in lithology and microfossil content of the marsh deposits, or the occurrence of lungfish burrows in the purple-mottled unit, are evidence of smaller-scale seasonal variations in climate that affected the depositional system. The abundance of wetland marsh and bog environments, fossil ferns, and giant horsetails 30 cm in diameter indicate there was abundant water in the system with water tables near or above the ground surface for much of the time. The lungfish burrows associated with gleyed paleosols indicate that there was seasonal flooding and variation in the moisture supply. The persistent occurrence of lungfish burrows up into the Petrified Forest and Owl Rock Members indicates that the climate was wet and stable enough to support lungfish in extensive lacustrine and marsh habitats until deposition of the Church Rock Member.

The occurrence of fossil vertebrates, invertebrates, and plants in the Chinle strata (Dubiel 1983b, 1984, 1987) afford independent but complimentary interpretations of depositional environments and paleoclimate of the enclosing rocks (Parrish and Good 1987; Good et al. 1987). The inferred habitats of metoposaurs and phytosaurs support interpretations of extensive aquatic environments, and in fact, indicate that many of these must have been perennial. The perennial nature of at least the Moss Back fluvial systems is suggested by the occurrence of thick-shelled, nonaestivating unionids in Moss Back crevasse splay deposits (Good et al. 1987). Thin-shelled, lacustrine unionids support sedimentologic interpretations for Monitor Butte and Petrified Forest lakes. Paleobotanical evidence is interpreted to indicate wet or humid tropical conditions (Ash 1972, 1978; Gottesfeld 1972). Aside from the actual character of the plants, their preservation as carbonized remains and sediment-filled pith casts indicate conditions of rapid burial beneath the water table.

Finally, the coloration of the rocks, which is a reflection of present hematite content and original and present organic-carbon content, and the paleosol development yield additional insight into water table fluctuations and climate. Gray, black, and green colors of the Monitor Butte Member reflect its high organic-carbon content that was the result of rapid sedimentation and preservation in subaqueous environments or below the water table and removal from the oxidizing effects of the atmosphere. Well-developed paleosols would not be expected in these subaqueous environments. However, seasonally flooded floodplains or

lacustrine mudflats would be expected to display some effects of pedogenesis. The color-mottling in the PMU is the result of pedogenesis, including both precipitation of hematite under alternating reducing and oxidizing conditions in the presence of organic matter, and of lungfish bioturbation. The redox conditions and the bioturbation reflect the fluctuating water tables present in the environment. The development of singular, isolated carbonate nodules in Chinle vertisols probably reflect the seasonal influx of carbonate with precipitation or flooding. Black, organic-carbon-rich marsh mudstones indicate that water tables must have been consistently near the surface for the plants to grow and to preserve the organic matter in these environments.

The Petrified Forest Member exhibits primarily lavender coloration within fluvial channel and splay deposits and deeper red colors in floodplain deposits. Organic-carbon-rich mudstones are restricted in extent and thickness, and coalified plant material is rare. The distribution of carbon reflects the more variable water tables of the upper delta plain environment that were subjected to seasonal flooding but not to subaqueous conditions. More extensive oxygenated conditions resulted in a proportionately higher destruction of organic matter. Consequently, the lack of carbon has failed to inhibit the development of hematite and the rocks exhibit redder coloration related to deposition under more oxidizing conditions that were the result of periodic subaerial exposure.

In the Owl Rock Member, low rates of clastic sedimentation under oxygenated lacustrine water columns led to the destruction of any organic carbon that may have been deposited in that environment. Thus, the development of carbonate sediments and hematite cements resulted in limestone beds and red siltstones, respectively. Similarly, deposition on essentially subaerial or ephemerally wet playa mudflats is responsible for the red coloration of the Church Rock Member. An important point is that the increased development of red coloration in the upper members of the Chinle is the result of increased development of diagenetic hematite. Eh-pH considerations (Garrels and Christ 1965) demonstrate that hematite can form in either an oxidizing or a reducing environment dependent upon pH, so that hematite formation by itself does not indicate an arid environment. Hematite could have formed in a subaqueous environment if the water was alkaline enough. While alkalininty may reflect aridity, it is not a prerequisite.

CONCLUSIONS

Sedimentologic considerations of the Chinle Formation in southeastern Utah provide insight into paleoclimate from the standpoint of depositional environments, organic-carbon preservation, water table position and fluctuation, and included fossils and trace fossils. Early in the history of Chinle deposition, water was abundant in the system. Wetland, lacustrine, and terrestrial environments supported aquatic and terrestrial fauna and flora. During deposition of the upper members of the Chinle, drier and more oxidizing conditions were prevalent, and these too are reflected in the depositional environments, lack of organic matter, and correspondingly lower water tables.

The identified depositional environments and paleosols suggest that although water was relatively abundant in the depositional system, it was punctuated by seasonally dry periods. Paleomagnetic reconstructions place this portion of the Colorado Plateau within the tropics during the Late Triassic, and the climate can be characterized as tropical monsoonal. This interpretation is consistent with independent evidence from paleontology, paleobotany, and paleoclimatic models.

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