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TAPHONOMY OF FOSSIL PLANTS IN THE
UPPER TRIASSIC CHINLE FORMATION

by

Timothy Michael Demko

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A Dissertation submitted to the Faculty of the
DEPARTMENT OF GEOSCIENCES
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
in the Graduate College
THE UNIVERSITY OF ARIZONA

1995
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Timothy Michael Demko entitled Taphonomy of Fossil Plants in the Upper Triassic Chinle Formation and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

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Dissertation Director

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# TABLE OF CONTENTS

1. LIST OF ILLUSTRATIONS .................................................. 8

2. LIST OF TABLES .......................................................... 10

3. ABSTRACT ............................................................... 11

4. INTRODUCTION .......................................................... 12
   Literature Review and Statement of Problem .................... 12
   Introduction .......................................................... 12
   Pangean Paleoclimate and the Chinle Formation ............... 14
   Overview of the Stratigraphy, Sedimentology, and
   Paleontology of the Chinle Formation ......................... 16
   Stratigraphy ......................................................... 16
   Sedimentology/Facies Analysis ................................. 18
   Paleontology ....................................................... 20
   Summary ............................................................ 21
   Taphonomic Studies of Fossil Plants ......................... 24
   Taphonomic Processes ........................................... 24
   Applicability of Phytotaphonomy to
   Environmental Interpretation ................................. 27
   Determinations of Regional Vegetation for
   Climatic Interpretations .................................... 29
   Determinations of Local Vegetation for
   Ecological Interpretations .................................. 33
   Determinations of Life Habitat and the
   Environmental Conditions of Fossilization ............... 34
   Examples of application of taphonomy to
   Environmental/Climatic Interpretation ................. 34
   Application of Plant Taphonomy to the Chinle
   Formation .......................................................... 37
   Methods ............................................................. 38
   References Cited .................................................. 45
   Explanation of Thesis Format ................................ 62

5. PRESENT STUDY .......................................................... 63
### TABLE OF CONTENTS — Continued

**APPENDIX A: SEDIMENTOLOGY AND PLANT TAPHONOMY OF A CHANNEL AND OVERBANK SYSTEM, UPPER TRIASSIC CHINLE FORMATION, PETRIFIED FOREST NATIONAL PARK**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>65</td>
</tr>
<tr>
<td>Introduction</td>
<td>65</td>
</tr>
<tr>
<td>Previous Work</td>
<td>70</td>
</tr>
<tr>
<td>Depositional Environments</td>
<td>72</td>
</tr>
<tr>
<td>Channel Fill/Lateral Accretion Deposits</td>
<td>73</td>
</tr>
<tr>
<td>Interpretation</td>
<td>78</td>
</tr>
<tr>
<td>Levee Deposits</td>
<td>80</td>
</tr>
<tr>
<td>Interpretation</td>
<td>80</td>
</tr>
<tr>
<td>Crevasse Splay Deposits</td>
<td>82</td>
</tr>
<tr>
<td>Interpretation</td>
<td>84</td>
</tr>
<tr>
<td>Paludal/Distal Splay Deposits</td>
<td>86</td>
</tr>
<tr>
<td>Interpretation</td>
<td>86</td>
</tr>
<tr>
<td>Distal Overbank Paleosols</td>
<td>87</td>
</tr>
<tr>
<td>Interpretation</td>
<td>87</td>
</tr>
<tr>
<td>Plant Taphonomy</td>
<td>89</td>
</tr>
<tr>
<td>Channel Fill/Lateral Accretion</td>
<td>89</td>
</tr>
<tr>
<td>Interpretation</td>
<td>91</td>
</tr>
<tr>
<td>Crevasse Splay</td>
<td>91</td>
</tr>
<tr>
<td>Interpretation</td>
<td>92</td>
</tr>
<tr>
<td>Paludal/Distal Splay</td>
<td>92</td>
</tr>
<tr>
<td>Interpretation</td>
<td>95</td>
</tr>
<tr>
<td>Discussion</td>
<td>95</td>
</tr>
<tr>
<td>Summary</td>
<td>102</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>103</td>
</tr>
<tr>
<td>References Cited</td>
<td>104</td>
</tr>
</tbody>
</table>

**APPENDIX B: TAPHONOMY OF FOSSIL PLANTS IN THE UPPER TRIASSIC CHINLE FORMATION, COLORADO PLATEAU, U.S.A.**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>108</td>
</tr>
<tr>
<td>Introduction</td>
<td>108</td>
</tr>
<tr>
<td>Chinle flora</td>
<td>110</td>
</tr>
<tr>
<td>Tectonic, climatic, and depositional setting</td>
<td>111</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS — Continued

Plant-bearing units .................................. 114
  Low-sinuosity channel PBU’s .................. 116
  High-sinuosity channel PBU’s ............... 123
  Abandoned-channel PBU’s ..................... 128
  Crevasse-splay PBU’s .......................... 132
  Lacustrine-delta PBU’s ......................... 141
  Paludal-overbank PBU’s ......................... 143
  Paleosol PBU’s .................................. 149
Summary and Discussion ............................ 152
References Cited .................................. 160

APPENDIX C: INCISED-VALLEY FILLS AND THE
TAPHONOMY OF FOSSIL PLANTS: AN
EXAMPLE FROM THE UPPER TRIASSIC
CHINLE FORMATION, COLORADO
PLATEAU, U.S.A. .................................. 169
  Abstract ....................................... 169
  Introduction .................................... 169
  Geologic setting ............................... 170
  Incised-valley fills in the Chinle Formation ... 172
  Distribution and taphonomy of fossil plants ... 178
  Discussion and Conclusions .................... 181
  Acknowledgments ............................... 186
  References Cited ............................... 186

APPENDIX D: MEASURED STRATIGRAPHIC SECTIONS .... 194

APPENDIX E: TABLES OF SEDIMENTOLOGIC AND
TAPHONOMIC DATA ................................. 267
LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chinle Formation stratigraphic correlation chart</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>Taphonomic variables in vertebrate assemblages</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>Graphic method of comparative taphonomy</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>Form for summary of plant taphofacies</td>
<td>44</td>
</tr>
<tr>
<td>A1</td>
<td>Petrified Forest National Park location map</td>
<td>67</td>
</tr>
<tr>
<td>A2</td>
<td>Composite section of Chinle Formation</td>
<td>69</td>
</tr>
<tr>
<td>A3</td>
<td>Location of measured sections</td>
<td>71</td>
</tr>
<tr>
<td>A4</td>
<td>Measured stratigraphic sections</td>
<td>74</td>
</tr>
<tr>
<td>A5</td>
<td>Panel diagram of fluvial and overbank deposits</td>
<td>75</td>
</tr>
<tr>
<td>A6</td>
<td>Exhumed lateral accretion sets</td>
<td>76</td>
</tr>
<tr>
<td>A7</td>
<td>Rose diagrams of paleocurrent directions</td>
<td>77</td>
</tr>
<tr>
<td>A8</td>
<td>Logs in base of lateral accretion deposits</td>
<td>79</td>
</tr>
<tr>
<td>A9</td>
<td>Interfingering channel, levee, and paludal deposits</td>
<td>81</td>
</tr>
<tr>
<td>A10</td>
<td>Crevasse splay deposits</td>
<td>83</td>
</tr>
<tr>
<td>A11</td>
<td>Neocalamites fossils</td>
<td>85</td>
</tr>
<tr>
<td>A12</td>
<td>Alluvial paleosols</td>
<td>88</td>
</tr>
<tr>
<td>A13</td>
<td>Erect stump in paludal/distal splay deposits</td>
<td>94</td>
</tr>
<tr>
<td>A14</td>
<td>Paleogeographic reconstruction</td>
<td>101</td>
</tr>
<tr>
<td>B1</td>
<td>Map of study area and plant localities</td>
<td>109</td>
</tr>
<tr>
<td>B2</td>
<td>Stratigraphic column of Chinle Formation</td>
<td>112</td>
</tr>
<tr>
<td>B3</td>
<td>Low-sinuosity channel deposits</td>
<td>117</td>
</tr>
<tr>
<td>B4</td>
<td>Map of logs in Shinarump Member</td>
<td>119</td>
</tr>
<tr>
<td>B5</td>
<td>Rose diagrams of log orientations</td>
<td>121</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS — Continued

FIGURE B6, Depositional model of low-sinuosity channel PBU's .... 124
FIGURE B7, Outcrops of high-sinuosity channel deposits ............. 125
FIGURE B8, Logs from high-sinuosity channel PBU's .................. 127
FIGURE B9, Depositional model of high-sinuosity channel PBU's .... 129
FIGURE B10, Outcrop of abandoned channel deposits ................. 131
FIGURE B11, Depositional model of abandoned-channel PBU's ...... 133
FIGURE B12, Outcrop of crevasse splay deposits ..................... 134
FIGURE B13, Neocalamites leaf litter .................................. 136
FIGURE B14, Depositional model of crevasse splay PBU's .......... 138
FIGURE B15, Erect stump from Black Forest bed ..................... 140
FIGURE B16, Lacustrine delta deposits, White Canyon, UT .......... 142
FIGURE B17, Depositional model of lacustrine delta PBU's .......... 144
FIGURE B18, Paludal-overbank deposits, Petrified Forest NP ...... 145
FIGURE B19, Coal seam, Monitor Butte Member ...................... 146
FIGURE B20, Plant fossils from paludal-overbank PBU's ............ 148
FIGURE B21, Depositional model of paludal-overbank PBU's ...... 150
FIGURE B22, Permineralized woody material from paleosol PBU's .. 151
FIGURE B23, Depositional model of paleosol PBU's ................. 153
FIGURE B24, Summary of PBU's ....................................... 156
FIGURE C1, Paleogeographic map of Chinle depositional basin ...... 171
FIGURE C2, Cross sections of lower part of Chinle Formation ...... 174
FIGURE C3, Summary of sedimentology and taphonomy .............. 179
FIGURE C4, Typical fossil plants ...................................... 180
FIGURE C5, Schematic cross-section of paleovalley during infill .... 185
LIST OF TABLES

TABLE 1, Depositional environments of Chinle Formation ........ 17
TABLE 2, Paleoclimatic indicators in the Chinle Formation ...... 20
TABLE A1, Fossil plants in crevasse and distal splay deposits ..... 68
TABLE A2, Summary of taphonomy of fossil plants ............... 90
TABLE A3, Paleohydraulic parameters of the Newspaper channel ... 97
TABLE B1, Log orientations and paleocurrent measurements ....... 120
ABSTRACT

Fossil plants in the Upper Triassic Chinle Formation are preserved in fluvial channel, overbank, and lacustrine deposits. Plant-bearing units in these deposits are classified into seven types based on these depositional environments or subenvironments. Taphonomic characteristics of these assemblages, and of individual plant fossils within them, indicate that most plant fossils have either not been transported far from their growth sites or are preserved in situ. One particular deposit in the central part of Petrified Forest National Park preserves fossil plants in three associations: 1) allochthonous logs in basal lags in a channel-fill/lateral accretion deposits; 2) autochthonous horsetail trunks and paraautochthonous horsetail leaves in a crevasse-splay deposits; and 3) paraautochthonous and autochthonous cycadaceous, fern and other types of leaves, and erect and prostrate trunks in a paludal/distal splay deposits. Exposures of contemporaneous high-sinuosity channel and overbank deposits in this area enabled the reconstruction of the local paleogeography, paleohydrology, and paleoecology at a high resolution. Fossil plant assemblages of the Upper Triassic Chinle Formation are concentrated in the lower members of the formation. The lower part of the Chinle Formation was deposited in an incised valley system. Depositional, hydrological, and near-surface geochemical conditions in the incised valley system were conducive to preservation of terrestrial organic material, even though regional conditions were characterized by seasonal/monsoonal precipitation and groundwater conditions. Fossil plant assemblages preserved in these types of fully terrestrial incised valley-fills are taphonomically biased towards riparian wetland environments.
Literature Review and Statement of Problem

Introduction

The Upper Triassic (Carnian-Norian) Chinle Formation is a colorful sequence of mudstone, siltstone, sandstone, and limestone extensively exposed on the Colorado Plateau. Recently, Dubiel and others (1991) described numerous features of the Chinle Formation as evidence that the sediments were deposited in a monsoonal regime, with high temperature and high, but strongly seasonal, rainfall. However, apart from presenting some preliminary information on growth rings in fossil wood, Dubiel and others (1991) did not incorporate information from the extensive plant fossil record in the Chinle.

The most famous fossils in the Chinle Formation are the permineralized logs found in Petrified Forest National Park, but other plant fossils are locally abundant there and elsewhere in the Chinle Formation. The systematics of the plant fossils have been described extensively by Ash (1967-1991), but relatively little work has been done on the climatic or sedimentologic signals recorded by the plants. Although some morphological features of plant fossils, such as growth rings in woods or cuticular structure, can be useful as direct indicators of climate, recent developments in plant taphonomy have shown that taphonomic information is crucial to interpreting fossil-plant ecology in its broadest sense.

Interpretation of the ecological roles of individual taxa and the determination of ancient community structures from fossil-plant assemblages must be made through taphonomic filters. Many phytotaphonomic investigations have concentrated on taphonomic biases,
examining how representative fossil floras are of the original plant communities. However, taphonomic studies of fossil plants also can provide information on the physical environment and climate in which they grew and the depositional setting in which they were preserved. For example, in conjunction with other information, concentrated fossil leaf mats, in which all the leaves are in the same state of preservation, are evidence of synchronous leaf fall, which has implications for the climatic conditions that the plants had to tolerate (White and Yeates, 1976; Spicer and Parrish, 1986). Detailed reconstructions and interpretations of terrestrial depositional environments hinge upon the determination of factors responsible for the incorporation of plant parts into a sedimentary deposit, such as relative autochthony/allochthony of plant parts and transport and burial processes. Preservational modes of fossil plant material, such as silicification, coalification, and casting, can offer clues to surficial, pedogenic, and later diagenetic conditions in the depositional basin.

This dissertation project had two related objectives: 1) to apply taphonomic studies of the fossil flora to resolve controversies over the Chinle-time climate and physical environment; and 2) to demonstrate the applicability of plant taphonomic methods in an environment that has not previously been investigated (see section on plant taphonomy).

This introductory chapter to the dissertation will: 1) review previous studies of Pangean paleoclimate, especially those that pertain to the Chinle Formation; 2) summarize previous work on the stratigraphy and sedimentology of the Chinle Formation; 3) summarize and discuss the taphonomy of fossil plants and its use in paleoenvironmental, paleoclimatic,
and paleoecologic interpretation; and 4) discuss the research methodology used in this study.

**Pangean Paleoclimate and the Chinle Formation**

Robinson (1973) first described the climate of the supercontinent Pangea as monsoonal based on the global distribution of red beds, evaporites, and coals in Triassic rocks. This confirmed Briden and Irving's (1964) conclusion that paleoclimatically significant rocks are not distributed in simple latitudinal zones. The monsoon concept had appeared previously in different forms to describe Triassic climate. For example, Daugherty (1941) described the flora of the Chinle Formation as "savannah", a term that refers to grasslands today. Most modern savannah is within the region of influence of the Asian monsoon (Rumney, 1968; Espenshade and Morrison, 1978), and always in areas of strong seasonality of precipitation.

The theoretical basis for Pangean monsoonal circulation has been established in a series of papers outlining the overall mechanisms (Parrish and others, 1982, 1986), monsoonal development (Rowley and others, 1985; Parrish, 1994), the monsoonal maximum (Parrish and Peterson, 1988), and the eventual breakdown of the monsoon (Parrish, 1993). Numerical models of Pangean paleoclimate support the interpretation of a monsoon-dominated circulation system (Crowley and others, 1989; Kutzbach and Gallimore, 1989).

In the Late Paleozoic, as Pangea moved north and the land area was distributed more evenly on either side of the equator, seasonality would be expected to have become stronger, and the equatorial region and mid-latitude continental interiors drier (Parrish, 1985; Parrish and others, 1986; Parrish
and Peterson, 1988; Dubiel and others, 1991). During the Triassic, the monsoonal circulation would have been at maximum strength, and aridity of the continental interior would have been greatest and the climate would have been characterized by highly seasonal rainfall (Dubiel and others, 1991).

The Chinle depositional basin was located at the southwestern margin of the North American plate, at or near the equator (Bazard and Butler, 1991). The Triassic was the time of greatest evaporite formation worldwide (Gordon, 1975), but on the Colorado Plateau, in westernmost Pangea, the Triassic was the wettest part of the Pangean continent, shifting from evaporite and eolian deposition in the Pennsylvanian and Permian, to fluvial and lacustrine deposition in the Triassic, and back to eolian deposition in the Jurassic (e.g., Peterson, 1988). Eolian sandstones deposited on the Colorado Plateau during the Late Triassic and Early Jurassic show a change in wind direction to east-southeast from the predominately south-southwest winds of the rest of the time of Pangean assembly and disassembly (except the Late Jurassic, when Pangaea had moved far enough north to be in the belt of westerlies; Peterson, 1988). Based on this shift, and the character of the depositional systems of the Chinle Formation, Parrish and Peterson (1988) suggested that monsoonal circulation was strong enough at this time to influence circulation on the western side of Pangaea and draw moisture along the equator from the west. Thus, the Chinle Formation has played a key role in hypotheses about the development of the Pangean monsoonal system.
Overview Of the Stratigraphy, Sedimentology, Paleontology of the Chinle Formation

**Stratigraphy**

The Chinle Formation is divided into a number of members (Figure 1) (Stewart and others, 1972). These members form a complex mosaic of facies, laterally interfingering with each other and pinching out across the basin (Blakey and Gubitosa, 1983; Dubiel, 1987a). The Chinle is over 500 m thick in the center of the depositional basin in south-central Utah, and thins to the east over the Ancestral Rocky Mountains, where it is erosionally truncated. To the southeast, it is correlative to the Dolores and Dockum Formations and, to the northeast, the Popo Agie Formation (Stewart and others, 1972). The relationship of the Chinle to marine Triassic rocks to the west is still problematic. In most places, the Chinle overlies the major regional Tr-3 unconformity (Stewart and others, 1972; Pipiringos and O'Sullivan, 1978). The lower part of the Chinle Formation is characterized by reddish brown and gray bentonitic mudstone and siltstone, coarse- to fine-grained, crossbedded sandstone, and conglomerate (Stewart and others, 1972). This lower part is divided into the Shinarump, Monitor Butte, Moss Back, and Petrified Forest Members. The upper part of the Chinle is characterized by reddish-brown siltstone and minor amounts of limestone and limestone-pebble conglomerate (Stewart and others, 1972). This upper part is divided into the Owl Rock, Church Rock, and Rock Point Members in the southern Colorado Plateau region (Stewart and others, 1972). Where recognized in northern Utah and Colorado, the Chinle is divided into
Figure 1. Stratigraphic correlation chart of members of the Upper Triassic Chinle Formation (from Stewart and others, 1972).
the Gartra, Mottled, Ochre Siltstone, and Siltstone Members (Stewart and others, 1972).

The lithofacies and depositional environments of the Chinle Formation in northern Arizona and southern Utah are summarized in Table 1, from Dubiel and others (1991). Plants are known from the Shinarump (Daugherty, 1941; Stewart and others, 1972; Ash and others, 1982; Ash, 1977, 1985), Monitor Butte and Petrified Forest Members (Daugherty, 1941; Ash, 1970a, 1975, 1985, 1989; Ash and others, 1982; Dubiel and others, 1991), as well as from the geographically restricted Temple Mountain Member of the San Rafael Swell region in Utah (Stewart and others, 1972; Ash, 1975) and Agua Zarca Sandstone Member of north-central New Mexico (Stewart and others, 1972; Ash, 1974b).

Sedimentology/Facies Analysis

Dubiel (1987a,b) and Dubiel and others (1991) described the general depositional systems that were present in the Chinle depositional basin and discussed the implications for paleoclimatic interpretations (Table 1). Dubiel (1987a,b) described terrestrial environments with abundant evidence for widespread wet environments (wetlands, lakes, floodplains, braided and meandering streams), but he also found features suggestive of repeated desiccation and lowered groundwater tables. Key features indicative of dry or seasonally dry climate are: (1) gleyed paleosols formed by fluctuating water tables; (2) floodplain vertisols containing abundant pedogenic carbonate nodules and pseudo-anticlines, strongly oxidized (and barren of plant material) where the soils were above the water table; and (3) desiccation cracks in the upper part. In summary, much of the basin was close to the
TABLE 1—Lithofacies and depositional environments of the Chinle Formation, Four Corners region.

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<tr>
<th>Stratigraphic unit</th>
<th>Lithofacies</th>
<th>Depositional environment</th>
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<tr>
<td>Church Rock Member</td>
<td>Orange to red and brown sandstone, siltstone and mudstone, with minor limestone; locally has large-scale lateral accretion bedding</td>
<td>Lacustrine and fluvial mudflats; minor high-sinuosity fluvial systems; eolian sand sheets</td>
</tr>
<tr>
<td>Owl Rock Member</td>
<td>Pink to gray and green limestone; red and orange sandstone, siltstone, and mudstone</td>
<td>Lacustrine basin and lacustrine mudflats</td>
</tr>
<tr>
<td>Petrified Forest Member</td>
<td>Lavender to red and brown sandstones and variegated mudstones; large-scale crossbedding and lateral accretion bedding; local carbonate nodules and black, organic-rich mudstones</td>
<td>Fluvial channels and point bars; paleosols and minor lacustrine marshes</td>
</tr>
<tr>
<td>Moss Back Member</td>
<td>Brown to gray sandstone and nodule-bearing conglomerate; minor red mudstone with carbonate nodules</td>
<td>Low-sinuosity fluvial channels; floodplains with calcic and vertic paleosols</td>
</tr>
<tr>
<td>Monitor Butte Member</td>
<td>Gray to green sandstone, siltstone, and mudstone; tan limestone; black, organic-rich mudstone</td>
<td>Fluvial and crevasse-splay channels; lacustrine deltas and marshes</td>
</tr>
<tr>
<td>Shinarump Member</td>
<td>Yellow to gray sandstone and conglomerate with minor gray mudstone; large-scale crossbedding; fills scours and paleovalleys</td>
<td>Fluvial channels and valley fills</td>
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</tbody>
</table>
water table throughout Chinle deposition, but those parts that were better drained show strong evidence of fluctuating water tables (Dubiel 1987a; Dubiel and others, 1991).

Blakey and Gubitosa (1983, 1984) and DeLuca and Eriksson (1989) concentrated on fluvial deposits in the Chinle. They concurred that climate had to have been warm and seasonal with respect to rainfall, although Blakey and Gubitosa (1983, 1984) suggested that changes in fluvial depositional styles vertically through the Chinle partly reflect changes in basin subsidence rate. Blakey and Gubitosa (1984) suggested that the surrounding highlands must have been humid, in order to supply the perennial streams with water. Rainfall in the source area need not have been constant to maintain perennial streams, so long as total annual precipitation was high, but the perennial streams in a highly seasonal climate would have experienced strongly fluctuating discharge (Coleman, 1969). A wet source region is not inconsistent with the monsoon hypothesis because mountains usually are wetter and total annual rainfall in a monsoon system, though extremely seasonal, is also high compared with other climatic regimes (Dubiel and others, 1991). DeLuca and Eriksson's (1989) study showed that perennial and ephemeral streams coexisted in the Chinle, precisely the pattern observed in regions with abundant, but highly seasonal, rainfall.

Paleontology

The first full description of the major elements of the fossil flora of the Chinle was published by Daugherty (1941). Subsequently, voluminous and detailed work by Ash (1967-1991) has revealed the full extent and diversity of the flora, which includes pterophytes, sphenophytes, cycadophytes, and
coniferophytes. Daugherty (1941) also noted that growth rings preserved in the permineralized logs were evidence of some sort of seasonality in the climate (see also Dubiel and others, 1991), and that the Chinle flora compared well to modern savannas. By contrast, Ash (1967, 1972a, 1978; Ash and Creber, 1990) favored everwet (i.e., rainforest, S.R. Ash, 1972b; see also Ziegler, 1990) conditions, based principally on comparisons with the habitats of nearest living relatives, general leaf physiognomy, and cuticles (Ash, 1978). At the other extreme to Ash's views, Gottesfeld (1972) regarded the climate of the Chinle as predominantly arid.

The invertebrate and vertebrate faunas and the trace fossils have contributed to the interpretation of the Chinle Formation as having been deposited in a seasonal environment (Dubiel and others, 1991). For example, Dubiel and others (1991) interpreted growth banding in the shells of the bivalves as indicative of seasonal variations in growth rate. Dubiel and others (1987, 1991) and Parrish (1989) suggested that the deep (> 2 m) lungfish and crayfish burrows (Dubiel and others, 1987; Hasiotis and Mitchell, 1989) may indicate a high range and repeated cycles of water table fluctuation owing highly seasonal precipitation. The trace fossil Scoyenia, abundant in the Chinle, also commonly occurs in shallow lake deposits subject to periodic drying (Ekdale and others, 1984).

Summary

Table 2 summarizes information that has been used to interpret the climate during deposition of the Chinle Formation. Two items warrant particular discussion. First, the studies of wood structure by Ash and Creber (1990) were done on wood from the bases of in situ trunks. They were trying to
### Sediments

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Interpretation</th>
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</thead>
<tbody>
<tr>
<td>paleosols&lt;sup&gt;1&lt;/sup&gt;</td>
<td>seasonally fluctuating water table&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>reddening, gleying, carbonate nodules, vertisols</td>
<td>marshes</td>
</tr>
<tr>
<td>(pseudoanticlines and pseudoslickensides)</td>
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<tr>
<td>organic-rich layers</td>
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<tr>
<td>abundance of redbeds&lt;sup&gt;2&lt;/sup&gt;</td>
<td>arid climate&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>presence of gypsum, evidence for fire&lt;sup&gt;3&lt;/sup&gt;</td>
<td>distinct dry season&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>fluvial architecture--mixture of perennial and braided stream deposits&lt;sup&gt;4&lt;/sup&gt;</td>
<td>seasonal rainfall&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
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### Animals<sup>5</sup>

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Interpretation</th>
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</thead>
<tbody>
<tr>
<td>bivalves with growth bands</td>
<td>seasonal fluctuations in water supply drying following flooding</td>
</tr>
<tr>
<td><em>Coelophysis</em> necks recurved</td>
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### Plants

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<th>Evidence</th>
<th>Interpretation</th>
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<tr>
<td>fossil trees with growth rings&lt;sup&gt;6&lt;/sup&gt;</td>
<td>seasonality of rainfall&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>fossil trees with no growth rings&lt;sup&gt;7&lt;/sup&gt;</td>
<td>humid climate&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>thin cuticles&lt;sup&gt;8&lt;/sup&gt;</td>
<td>humid climate&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>ecology of nearest living relatives&lt;sup&gt;8&lt;/sup&gt;</td>
<td>humid, warm climate&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>all leaves except conifer and one fern are broad&lt;sup&gt;9&lt;/sup&gt;</td>
<td>humid, warm climate&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>high diversity&lt;sup&gt;10&lt;/sup&gt;</td>
<td>humid, warm climate&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
</tbody>
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<sup>1</sup>Dubiel, 1987a,b; Dubiel and others, 1991
<sup>2</sup>Daugherty, 1941; Gottesfeld, 1972
<sup>3</sup>Daugherty, 1941
<sup>4</sup>DeLuca and Eriksson, 1989
<sup>5</sup>Dubiel et al., 1991
<sup>6</sup>Daugherty, 1941; Gottesfeld, 1972; Dubiel and others, 1991
<sup>7</sup>Ash and Creber, 1990
<sup>8</sup>Ash, 1972b, 1977, 1978
<sup>9</sup>Ash, 1972b, 1989
<sup>10</sup>Ash, 1987b
avoid the possibility that the wood had been transported a significant distance. However, root wood and stem wood at the basal flare are poor recorders of climatic change (Fritts, 1976), and sometimes show no or indefinite rings, even if the stem wood has prominent rings. Dubiel and others (1991) disagreed with Ash and Creber's (1990) conclusion that the woods of Petrified Forest showed no seasonality, because growth rings are prominent in stem wood from other localities. Second, Ash (1972a, 1977, 1978) interpreted cuticle from leaves of the Chinle flora as thin and indicative of wet climate. However, the cuticle data may not be so conclusive. The preservation of cuticle at all implies a certain robustness, as paleofloras from clearly everwet environments are commonly not associated with cuticle, even when they are otherwise exquisitely preserved (e.g., Cretaceous floras of N Alaska; Spicer and Parrish, 1986). In addition, the cuticles described and figured by Ash (1970a, 1976, 1977, 1978, 1985; Ash and others, 1982) commonly have features such as sunken stomata; overlapping papillae; and hairs or other ornamentation, that are typical of (although not exclusive to) xeromorphic plants (Martin and Juniper, 1970; Cutler, 1982; Fahn, 1982; Thomas and Spicer, 1987; Wolfe and Upchurch, 1987a). On the other hand, the Chinle fern cuticles were similar to those from modern mesophytic environments (Ash, 1970b). In any case, with a high water table (Dubiel and others, 1991), the cuticle information may not be pertinent, particularly in those plants that could have died back every year. If this subject appears confusing, it is, and part of the goal of this study is to use taphonomic data to distinguish among the different strategies that plants utilized to cope with the environment.
Taphonomic Studies of Fossil Plants

Taphonomic Processes

Taphonomy is the study of the processes of preservation of fossil organisms and how these processes affect information in the fossil record (Behrensmeyer and Kidwell, 1985). Plant taphonomy is a relatively new subdiscipline, having been actively researched only in the last two decades (Spicer, 1989), and even then by relatively few practitioners. Thus, large gaps still exist both in the understanding of taphonomic processes that comes from studying those processes in modern environments and in the variety of geologic settings in which the taphonomy of fossil plants has been studied. With a few exceptions (e.g., Wing, 1984), taphonomic studies have been carried out in coastal-plain, generally wet-climate, coal-bearing sections.

Taphonomic processes can be subdivided into: 1) necrology; 2) biostratinomy; and 3) diagenesis (Gastaldo, 1988). Necrological factors involve plant death or the loss of plant parts. Both physiological loss, through the processes of growth, and traumatic loss, resulting from mechanical breakage by wind or water, contribute plant material to sediments. Burial of a plant in its growth site usually records the death of the plant. This may be the result of eolian (Chan, 1989), volcanicslastic (Dorf, 1964; Van Der Burgh, 1983/1984; Fritz, 1986; but see Coffin, 1983, and Fritz and Harrison, 1985), or fluvial (Featherly, 1941; Bryzyski and others, 1976; Hall and Lintz, 1983; Kraus, 1988) sedimentation.

Biostratinomy treats plant parts as sedimentary particles, and involves the transportation, burial, and ultimate incorporation of plant material into the sedimentary record. Fossil plant parts are autochthonous if
they are preserved in their original growth sites, parautochthonous if they have been transported <0.5 km from their growth sites, and allochthonous if they have been transported >0.5 km (Gastaldo, 1988). Examples of autochthonous plant fossils include roots, rhizomes, and erect, *in situ* tree trunks (Dorf, 1964; Gastaldo, 1986). Allochthonous plant fossils usually are transported by wind and/or water (transport by animals is possible, but so far undocumented in the fossil record).

Water is the principal means of plant part transport (Spicer, 1989). Plant material may be transported by normal stream flows and in great quantities by high-discharge events associated with floods. Most plant material is transported within the water column as suspended load. Leaves, seeds, branches, logs, and other woody material are transported at or slightly below the surface (Spicer, 1989). In contrast, sunken or waterlogged trunks and woody fragments are transported as bed load, and this material may be oriented parallel to stream currents (McDonald and Jefferson, 1985; Spicer, 1989). However, as the number of logs increases on the channel bottom, log jams may occur, resulting in oblique to perpendicular orientations with respect to currents (Degges and Gastaldo, 1988; Degges, 1991). Hollowed plant parts (stems, trunks) resident on the channel bottom or floodplain may be cast and molded by both suspended sediment (Gastaldo and others, 1989) and traction load (Rex, 1985; Degges and Gastaldo, 1988). Plant organs are degraded and sorted during transport (e.g., Chaney, 1924; Ozaki, 1969; Kaushick and Hynes, 1971; Spicer, 1981; Carpenter and Horowitz, 1988) and in lakes before burial (Rau, 1976; Spicer, 1981; Holyoak, 1984). Wind transport usually involves some sorting of small plant parts (spores, pollen,
seeds), and the transport distance is dependent on the aerodynamics (shape, surface-to-volume ratio) of these organs (Spicer, 1981).

**Diagenetic processes** affect plant fossils after burial. Geochemical conditions at and below the depositional surface control the extent of degradation and degree of preservation of incorporated plant material. The presence of aerobic detritivores, fungi, and bacteria is dependent on the depth, porosity, permeability, pore water pressure, and pCO₂ of the entombing sediments. Finer-grained sediments are more likely to preserve organic material than sand-sized and larger material.

Compaction can control the final appearance of the fossil (Rex 1985, 1986). Compaction will not occur if the fossil has been permineralized during very early diagenesis; it is common to see a range of compaction features in fossil wood from the same assemblage. In the middle Cretaceous rocks of Alaska, many logs were compacted and cell structure disrupted; those logs were probably waterlogged before burial (Parrish and Spicer 1988a). Similarly, logs in southern Petrified Forest National Park show a range of preservation and compaction that is roughly dependent on log diameter. Larger logs are compacted and the cell structure poorly preserved (Sigleo, 1979); in this case, permineralization appears to have been incomplete before deep burial.

The preservation mode of plant fossils is determined during early diagenesis. Biochemical alteration of carbon compounds within the plant structure determines if, and how much carbon is retained, and whether it is coalified or permineralized (Barghoorn, 1952). Permineralization involves the infiltration of mineral-rich fluids into woody plant tissues and subsequent
replacement of cell walls by precipitated authigenic minerals.

Permineralized wood is a fairly common fossil because of its structure—wood acts as a conduit for fluids during life, and retains this ability even after death. Silicification of wood, especially pertinent to this study, has been shown by Drum (1968) and Leo and Barghoorn (1976) to occur rapidly (1-3 weeks) under the right conditions.

Applicability of Phytotaphonomy to Environmental Interpretation

Spicer (1989) stressed that plants are not biologically stable through time. Species evolve and go extinct, and in the process, closely related taxa may develop quite different environmental tolerances. This is why paleoenvironmental interpretations based on taxonomic composition are so unreliable—except in the youngest fossil floras, the present is very likely not to be the key to the past (Wolfe, 1979). Wolfe (1979, 1990), drawing on earlier work by Bailey and Sinnott (1915, 1916), quantified the empirical relationship between certain attributes of modern vegetation and mean annual temperature and rainfall. The key attributes are morphological characteristics of angiosperm leaves, such as the type of margin (i.e., serrated, entire, etc.), and forest type. Wolfe (1979) showed that these relationships are functional, and thus was justified in applying them to the Tertiary fossil record. Taking the approach further back in time, Spicer and Parrish (1986) and Parrish and Spicer (1988b), noting that the major angiosperm tooth types had evolved by the middle Cretaceous, applied the approach to Cretaceous angiosperm-rich floras in Alaska. The estimates of mean annual temperature that they derived were supported by changes in the vegetational physiognomy and characteristics of growth rings in the fossil woods. It has
been elegantly demonstrated by Gastaldo (1987), studying Carboniferous and modern vegetation, that even the local structure of plant communities in fluvial environments is very similar through time, regardless of taxonomic composition.

Although the only quantitative method that has been developed to date for estimating mean annual temperature from plants is limited to floras that contain angiosperms, it is possible to derive relatively constrained qualitative estimates of climate from vegetation of any age by relying on the same principals of functional responses of vegetation to climate. General features, such as cuticle thickness, ornamentation, and stomatal density (e.g., Krasilov, 1975; Cutler, 1982; Wolfe and Upchurch, 1987a); presence of stilt-like roots and/or buttresses on stumps (Krasilov, 1975; Upchurch and Wolfe, 1987); liana-like habit (Krasilov, 1975; Upchurch and Wolfe, 1987); deciduousness (Wolfe, 1987; Spicer and Parrish, 1986; Parrish and others, 1991); and characteristics of growth rings and vessel dimensions in wood (Fritts, 1976; Creber, 1977; Creber and Chaloner, 1984; Wolfe and Upchurch, 1987b) provide information about water supply, temperature, seasonality, and light, especially when several taxa from the same flora share one or more features.

Although functional morphologic and physiognomic features to determine climate are extremely valuable for making environmental interpretations, those interpretations are very much enhanced by taphonomic information. Thus, for example, although Spicer and Parrish (1986) and Parrish and Spicer (1988b) were able to use leaf-margin analysis and the physiognomy of the vegetation to make estimates of mean annual temperature in the Late Cretaceous, their use of both methods was greatly
enhanced by taking taphonomic factors into account, as discussed later. Such factors included the sedimentary regime, states of preservation, and composition of each plant assemblage (*sensu* Spicer, 1989).

Application of taphonomy to environmental interpretation is useful at many levels of analysis, including determination of: 1) regional vegetation for the purpose of interpreting paleoclimate; 2) local vegetation for the purpose of interpreting paleoecology; and 3) life habits of individual plants and the sedimentological and paleoclimatic factors that contributed to patterns of preservation. Examples of each of these levels of analysis and how they have contributed to paleoclimatology, paleoecology, and sedimentology will be discussed in the following sections.

**Determinations of regional vegetation for climatic interpretations.** --A key element of paleoclimatic interpretations based on plants is understanding the physiognomy of the vegetation (Wolfe, 1979). Two major factors that control the formation of fossil-plant assemblages and that can impede interpretations of vegetational physiognomy are transport and environmental heterogeneity. A large number of observational and experimental studies have been carried out to determine the influence of transport on the formation of fossil assemblages (Spicer, 1989). Some key studies include those on leaves by Burnham (1989), who studied the relationship between the composition of leaf litter and that of the surrounding standing vegetation in a tropical forest; Spicer (1981), Spicer and Greer (1986), and Spicer and Wolfe (1987), who addressed the taphonomy of plant parts in modern lakes; and Ferguson (1985), who addressed transport of leaves in air (among other subjects). A common conclusion to all these studies is that leaf litter
represents the very local vegetation. For example, Ferguson (1985) observed that the majority of wind-blown leaves land within 50 m of the parent tree. In the delta of a small (13,000 m²) lake, Spicer (1981) found that leaves preserved in the topset sediments sampled the stream vegetation, whereas leaves in the bottomset sediments were, for the most part, from the lake-margin vegetation. In all these studies, leaves from farther away were strongly diluted by leaves from plants in the immediate vicinity of the sample site. It should be noted, however, that exceptions occur: Gastaldo and others (1987) found that leaves preserved in a crevasse splay deposit in the Mobile delta were dominated by "upland", rather than local plants, emphasizing the need for sampling all environments in order to characterize regional vegetation (Spicer and Parrish, 1986).

As a general statement, leaves are representative of the vegetation in the immediate drainage basin, and even within a drainage basin, the farther the plant grows from the site of deposition, the less likely it was to be represented (Spicer and Wolfe, 1987). Thus, although leaves do not suffer strongly from the effects of taphonomic processes such as sorting and long-distance transport, interpretation of the regional vegetation requires sampling all available local environments (see next section). Such sampling results in a leaf assemblage that is representative of the regional vegetation and its environmental, especially climatic, signal (Spicer, 1981; Spicer and Wolfe, 1987; Burnham, 1989). In addition, comparisons among assemblages can provide additional clues to the regional vegetation. Ubiquitous forms may indicate domination by those taxa (e.g., Podozamites in the Cenomanian flora of Alaska; Spicer and Parrish, 1986; Spicer, 1989).
Other plant organs, such as stems and, especially, seeds and pollen, are likely to be transported longer distances owing to their relative robustness, and Spicer and Parrish (1986) and Burnham (1990) encouraged use of seeds and pollen for environmental interpretations only in combination with data on leaves. In the Nanushuk Group (Albian-Cenomanian) in Alaska, pollen data (Shane, 1984; May and Shane, 1985) clearly show evidence of sorting, and thus the different pollen assemblages cannot represent original communities. Moreover, only ten forms of angiosperm pollen but more than 65 forms of angiosperm leaves have been reported. However, in the upper Colville Group (Campanian-Maastrichtian), pollen forms were much more diverse than leaf forms, leading Spicer and Parrish (1990a) to conclude that the pollen there probably represented herbaceous forms, which would be poorly preserved as megafossils. A high proportion of herbaceous plants would be consistent with the conclusion based on evidence from the megafossils that climate had cooled substantially by the latter part of the Cretaceous. Thus, although the use of pollen alone can lead to problems, pollen data are very usefully combined with megafossil data to provide a more complete picture of the composition of the vegetation. Burnham (1990) came to the same conclusion regarding the use of seeds and fruits in a study of modern environments in Belize. Although these organs were not representative of the vegetation on the island where they were sampled, they did complement the locally derived leaf data in providing a picture of the regional vegetation in the nearby islands and mainland.

Wood is very durable and easily transported, and for this reason Spicer (1989) cautioned that fossil wood found in marine sediments should not be
used for paleoenvironmental analysis; he pointed out that the beaches of the
treeless Aleutian Islands are strewn with logs, probably transported from
wooded regions far to the southwest. So long as wood is found in terrestrial
rocks, however, it must have been derived from the drainage basin, and its
representativeness of the environmental conditions at the sampling site
depends then on the extent of the basin.

In contrast to the extensive studies of leaf transport, little work has
been done tracking logs down rivers in order to quantify transport distances,
time, and damage. A general statement of wood transport is that its
effectiveness is dependent on the relationship of depth and channel roughness
to particle size (Spicer, 1989), and less on flow rates than previously assumed
(Spicer and Greer, 1986). Logs commonly are not transported far before they
encounter an obstacle, even in very large rivers (Spicer, 1989), but no data
exist to quantify how often those logs are buried or remobilized for further
transport downstream. Moreover, data on damage during transport also are
lacking, although abrasion can be identified readily in fossil wood, and the
presence of strongly protruding features such as branches and roots would
argue against long-distance transport.

Until the appropriate studies are carried out, the conservative
approach is to regard fossil wood data as representative of basin climate so
long as: 1) the wood comes from nonmarine sediments; 2) the paleoriver was
small (<500 km, or <1000 km if the river flowed approximately parallel to
latitude); 3) the drainage basin did not have significant topographic relief
(<1000 m); and 4) the wood is not significantly abraded. Greater differences
in transport distance and elevation introduce the possibility that the climate
in which the trees grew was different from that of the sampling site. Paleogeographic reconstructions that are sound enough to answer points 2 and 3 will not be possible for all basins, but should be for most. If possible, the wood should be compared with the local vegetation, to identify whether it is allochthonous. For example, Degges (1991) found that a Carboniferous logjam was dominated by *Cordaites* wood, which was not represented in the surrounding local vegetation. However, this type of comparison can only be made when the whole plant, including all its organs, can be reconstructed with some confidence. In practice, evidence supporting such reconstructions is uncommon.

*Determinations of local vegetation for ecological interpretations.*—One of the great strengths of combining paleontological and taphonomic data lies in the possibility of reconstructing local paleocommunities and determining the spatial structure and heterogeneity of the regional vegetation. Leaf fossils in any particular sample only the very local vegetation. In combination with data on the sedimentology and stratigraphy, detailed reconstructions of the vegetational mosaic are possible (Spicer and others, 1992). Nevertheless, some caution must be exercised, for the following reasons (Spicer, 1989): (1) The proportions of different leaf forms cannot be taken as reflecting the original proportions in the vegetation, owing to differential ease of preservation. (2) Although leaves are not easily transported before they break down, some sorting, particularly between needle-like leaves (e.g., conifer needles) and broad leaves (e.g., fern fronds) may occur. In those cases, the needles are nearly always associated with sedimentary evidence of current flow, such as ripple lamination, and thus can be avoided. If needles found in
such rocks are the only leaves found locally, the assumption cannot be made that angiosperms, ferns, or other broad-leaved plants were not present. Transported broad leaves are commonly rolled (Gastaldo, 1986, 1988; Spicer, 1989).

**Determinations of life habit and the environmental conditions of fossilization.**--The state of preservation of leaves and other plant fossils, including the rolling mentioned above, can provide valuable clues to sedimentological conditions, and sometimes to the ecology of the plants, both of which can aid in interpreting climate. Rolled leaves provide evidence for current transport, and leaves that are "draped" over nodules (Demko and Gastaldo, 1992; J.T. Parrish, personal communication) are evidence of very early cementation in the formation of those nodules. Microbial, invertebrate, and mechanical damage to leaves result in such characteristic features that they are easily distinguishable (Spicer, 1981; Hanlon, 1982); this has permitted confirmation of the intuitive conclusion that higher temperatures lead to faster biological degradation (Ferguson, 1985).

**Examples of application of taphonomy to environmental/climatic interpretation.**--Three examples illustrate particularly well the importance of taking advantage of taphonomic information for interpreting habit, ecology, and, subsequently, climate. In the first example, previous studies of the middle Cretaceous flora of Alaska had concluded that the flora contained evergreen elements, including cycads, which were popularly believed to be frost sensitive, and that the flora was warm temperate or subtropical (Smiley, 1966, 1967, 1969). At very high latitudes, such a vegetation is metabolically untenable because depletion of nutrients by respiration cannot
be offset by photosynthesis. Because northern Alaska's paleolatitude was well known within a few degrees, this led to suggestions that the Earth's obliquity was lower (Wolfe, 1971; Douglas and Williams, 1982), but that was climatically untenable because in that case, radiation of heat to space would have exceeded heat input by the sun, resulting in a cold climate (Barron, 1984). Thus, it became critical to reexamine the vegetation to confirm its ecology. Many of the plants, such as ferns and horsetails, are widely accepted to be annuals that die back to storage organs under adverse conditions, and these elements of the vegetation were not controversial. However, Spicer and Parrish (1986) were able to demonstrate that only one form, a microphyllous conifer, was probably evergreen. Microphyllly is a common strategy used by plants to survive adverse conditions; thus, modern cold-climate conifers are almost all evergreen, but also microphyllous, which allows them to avoid desiccation and freezing in the winter. All other forms in the middle Cretaceous vegetation of Alaska, including the rest of the conifers and the cycads (Kimura and Sekido, 1975), were deciduous. Although plants are usually referred to as being either deciduous or evergreen, all plants lose leaves during their life spans. In addition, some "evergreen" plants are facultatively deciduous, losing their leaves all at once if unusual adverse conditions, such as extreme drought or inundation by volcanic ash, arise (Burnham and Spicer, 1986). Therefore, in the fossil record, morphological characteristics such as the expanded base at the end of the petiole may not be diagnostic. Facultatively deciduous plants observed by Burnham and Spicer (1986) also are normally evergreen. Thus, Parrish and others (1991) now specify synchronous deciduousness (see also Thomas and Spicer, 1987) to
refer to plants that drop all their leaves in response to seasonal adverse conditions, and asynchronous deciduousness to refer to plants that are facultatively deciduous.

In the second example, Demko and Gastaldo (1992) documented the effects on Carboniferous swamp vegetation of compaction of peats by catastrophic influx of clastic sediments in floods. The clastic swamp deposits (Gastaldo, 1987) are underlain by coals; have multiple layers of disturbed vegetation, most of which is not found as part of the peat-swamp community; and are topped by more coal. The sequence of events reconstructed by Demko and Gastaldo (1992) was as follows: 1) inundation of the peat swamp by floodwaters, which deposited mud; 2) colonization of the mud by new plants and by some peat-swamp plants (mostly Calamites) that survived and grew up through the mud; 3) compaction of the peat, creating a new depositional low; 4) new influx of flood-borne sediment; 5) repeat of steps 3 and 4 ("punctuated loading"—note that compaction ratios for Carboniferous peats were 21:1 to 40:1; Winston, 1988) until the peat was relatively stable; 6) exclusion of clastic sediment, accumulation of organic matter, and reestablishment of the peat-swamp flora. This type of autocyclic mechanism had never been described before, and the taphonomic information, including the biostratinomy of in situ litter layers and standing vegetation, was critical to the interpretation.

The third example is from work by Wnuk and Pfefferkorn (1987), who also studied a Carboniferous swamp deposit. Among their findings was a unidirectional orientation of lycopod logs, contrasted with the random orientation of pteridosperm stems, all within a quiet-water, non-
volcaniclastic sediment. The only feasible explanation was that the forest consisted of lycopods with a pteridosperm understory and that the lycopod trunks had been toppled by unidirectional storm winds into the remains of the understory. As pointed out by Spicer (1989), neither the study of the sediments nor the fossils alone could have accounted for the pattern observed.

Application of Plant Taphonomy to the Chinle Formation

The forgoing discussion included the following types of taphonomic information that have proved useful in other regions and that have been applied in the Chinle in this study: 1) evidence and style of transport; 2) composition and states of preservation of plants in different environments; 3) preservation and transport of wood; 4) evidence of sorting; and 5) orientation and concentration of plant parts. Previous studies of plant taphonomy have concentrated principally on modern taphonomic processes of transport and leaf accumulation. However, nearly all that is known about the resulting stratigraphic patterns and the relationship between sedimentology and taphonomy has come from coal-bearing sequences (e.g., Wnuk and Pfefferkorn, 1987) or peat-rich environments (Pfefferkorn and others, 1988). The Chinle Formation was deposited in a tropical, equatorial setting. In this region, three potential climates could exist: everwet, mildly seasonal, and strongly seasonal rainfall. Today, vegetation in the first two climates is tropical and paratropical rainforest, respectively. Fluvial sedimentation tends to be largely from slow-flowing streams and the sediments are transported principally as suspension load; peat swamps are common, although not universal. Vegetation in monsoonal climates is typically savannah (which has no direct pre-Tertiary equivalent), mires are uncommon, and a high
proportion of fluvial sedimentation is from high bedload streams (Coleman, 1969). The taphonomic analysis of the fossil plant assemblages from the Chinle Formation undertaken in this study addressed the three levels of analysis discussed previously; that is determination of: 1) regional vegetation for the purpose of interpreting paleoclimate; 2) local vegetation for the purpose of interpreting paleoecology; and 3) life habits of individual plants and the sedimentological and paleoclimatic factors that contributed to patterns of preservation.

**Methods**

Field work involved detailed sedimentary facies analysis and description of fossil plant taphocoenoses (taphonomic assemblages of fossil material) at selected well-exposed outcrops of the Chinle, which together represented all of the environments found in the unit. Facies analysis in the plant-bearing sections included:

1. **Description of the lithofacies in plant-bearing sections.** Descriptions included composition, color, and texture of the rocks. Special attention was paid to paleosols, which provided important data on surficial conditions (climate, sedimentation rate, biological activity, etc.) and groundwater levels.

2. **Description and interpretation of sedimentary structures.** Cross bedding, bedding plane features, and syndepositional deformation features were described and interpreted with respect to paleohydraulics and paleocurrents.

3. **Determination of facies geometry and architecture.** Along with detailed sedimentologic and stratigraphic data, photomosaics of large-scale
facies distributions were constructed. This was done initially with Polaroid instant color prints, then later with black and white and color prints. Important bounding surfaces and facies designations were outlined directly on the Polaroid photomosaics, then transferred to the print photomosaics later. This technique has proved quite valuable in detailed facies analysis of extensive exposures of fluvial/alluvial deposits (Miall, 1988).

(4) Identification of plant remains. A field identification key for fossil plants was prepared to facilitate data collection at the outcrop. This key included representative illustrations of all figured fossil plant taxa from the Chinle and related formations, and is based primarily on the exhaustive published work of Dr. Sidney Ash.

Special emphasis was placed on describing the plant taphocoenoses, including:

(1) Detailed description of bedding features for each bed that contains fossil plant material. This included the extent, form, lithology, and thickness of the bed. As stated above, this facilitated treating plant-bearing units as additional elements in the facies architecture of the local depositional system. In addition, this contributed information on transport of the plant parts.

(2) Determination of the order and arrangement (random, mixed, oriented) and concentration (parts/m²) of preserved plant parts. Methods of determining concentration depended on the nature of the outcrop. If large blocks were available, or quarrying was possible, 0.5 meter-square quadrats were used along an appropriate spatial grid using the methods described in Spicer (1988). Where only small blocks were available or only small quarries
were feasible, 10 cm$^2$ quadrats were used (Pfefferkorn and others, 1971). As discussed in the previous section, the orientations of the leaves provided information about the transport and origin of the leaves.

(3) Assessment of the predominance of particular organs, i.e., relative abundances of stems, leaves, trunks, and rooting organs. This was expressed as ratios (e.g., stem:leaf) dependant on the range of organs preserved within the plant-bearing unit.

(4) Characterization of the nature of fossilization (compression, impression, adpression, and/or permineralization). Although the preservational mode was usually obvious in the field, representative samples were collected for further description. The degree and nature of any pre-burial damage to the plants was also be assessed. This was of aid in determining the relative importance of transport abrasion, herbivory, and/or fungal or microbial decay.

(5) Determination of autochthony, paraautochthony, or allochthony of material. The criteria used for assessing whether particular plant parts were in situ, proximal, or distal to their growth positions included the presence of attached rooting structures that cross-cut bedding, orientation of the plant parts within the strata, and relative amount of abrasion and other damage.

(6) Characterization of the diversity of the taxa preserved. This was evaluated by determining the number of dominant taxonomic elements represented in the assemblage. Estimates of frequency, density, and cover (as %) were used in determining these values (Spicer, 1988).

(7) Evaluation of community structure. An important part of this study was to determine the depositional environment of the plant-bearing units, so
it was logical to interpret the assemblage in a paleoecological context. This involved reconstructing the local paleogeography and paleo-groundwater conditions in order to place autochthonous and paraautochthonous taxonomic elements within ecological zones on the ancient landscape.

Comparative taphonomic studies were also carried out. Behrensmeyer (1991) has used a semi-quantitative graphical technique to compare vertebrate taphocoenoses with some success. Figure 2 (from Behrensmeyer, 1991) illustrates the data she used in quantifying vertebrate taphonomic evidence, and Figure 3 (from Behrensmeyer, 1991), shows how the information from four hypothetical taphocoenoses can be plotted to facilitate comparison. As noted by Behrensmeyer (1991), the connecting lines are only to aid visual comparison of patterns between the assemblages and to highlight the relative positions of neighboring variables. Clearly some of her data categories, for example, body size and age spectrum, were inappropriate for most plant taphonomic data, although tree size is important (Spicer and Parrish, 1990b). This system was adapted to compare the plant taphocoenoses described from the Chinle (Figure 4). As in Behrensmeyer's (1991) examples from vertebrate assemblages, the purpose of these diagrams is to summarize complex arrays of taphonomic information for each assemblage or taphofacies. The diagrams aid in visualizing the behavior of different taphonomic variables in relation to one another within and between assemblages. Site-selection criteria involved: 1) the presence of plant fossils; 2) the ability to view facies geometry in multiple dimensions; and 3) sampling of a wide range of interpreted environments, including examples of fluvial channel, overbank, abandoned channel, floodplain, marginal, paludal, and deltaic deposits.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Possible manifestation at a fossil site</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assemblage data</strong></td>
<td></td>
</tr>
<tr>
<td>Sample size</td>
<td>1 — — — — — — — 100 — — 1000 — — 10,000</td>
</tr>
<tr>
<td>Number of individuals</td>
<td>1 — — — — — — — 10 — — 100 — — — —</td>
</tr>
<tr>
<td>Number of species</td>
<td></td>
</tr>
<tr>
<td>Relative abundance</td>
<td>all individuals/one species equal no. of individuals/species</td>
</tr>
<tr>
<td>Body size (kg)</td>
<td></td>
</tr>
<tr>
<td>Age spectrum</td>
<td>juveniles only — — 50/50 — — — adults only</td>
</tr>
<tr>
<td>Bone articulation</td>
<td>articulated, disarticulated, associated + isolated +</td>
</tr>
<tr>
<td>Skeletal parts</td>
<td>unsorted — — sorted — — one part only</td>
</tr>
<tr>
<td><strong>Quarry data</strong></td>
<td></td>
</tr>
<tr>
<td>Size of accumulation</td>
<td>— — 1m² — — 100m² — — 1000m² — —</td>
</tr>
<tr>
<td>Spatial density</td>
<td>— — 0.1m² — — 1/m² — — 10/m² — — 100/m² — —</td>
</tr>
<tr>
<td>Spatial arrangement</td>
<td></td>
</tr>
<tr>
<td>In plan view</td>
<td>random — — — — preferred orientation</td>
</tr>
<tr>
<td>In profile</td>
<td>high dips — — — — — — horizontal</td>
</tr>
<tr>
<td>Patchiness</td>
<td>even — — — — uneven — — highly patchy</td>
</tr>
<tr>
<td><strong>Bone modification</strong></td>
<td></td>
</tr>
<tr>
<td>Breakage</td>
<td>complete — — — broken — — — fragments</td>
</tr>
<tr>
<td>Cracking</td>
<td>uncracked — — small cracks — — range of cracking</td>
</tr>
<tr>
<td>[Weathering according to Behrensmeyer (1978)]</td>
<td>Stage 0 — — Stage 1 — — Stages 0-3</td>
</tr>
<tr>
<td>Abrasion/polishing</td>
<td>unbraded — — abraded — — highly abraded</td>
</tr>
<tr>
<td>Surface marks</td>
<td>none — — — present — — extensive</td>
</tr>
<tr>
<td>(punctures, scratches, grooves, etc.)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Summary of taphonomic evidence used by Behrensmeyer (1991) in describing and comparing fossil vertebrate assemblages.
Figure 3. Example of a graphic summary and comparison of taphonomic variables used by Behrensmeyer (1991). Data is from two vertebrate assemblages from the Plio-Pleistocene Koobi Fora Formation of northern Kenya.
Figure 4. Form used in this study for graphic summary and comparison of plant taphofacies in the Chinle Formation. Based on form used by Behrensmeyer (1991) for vertebrate accumulations.
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Explanation of Dissertation Format

The following appendices consist of three manuscripts that form the bulk of this dissertation. The first paper, entitled *Sedimentology and plant taphonomy of a channel and overbank system, Upper Triassic Chinle Formation, Petrified Forest National Park*, is a detailed look at the depositional environments in a high-sinuosity channel and floodplain system, and where, how, and why fossil plants are preserved there. This area was chosen for detailed study because of the abundance of fossil plants found there and its heavily weighted importance in what is known about the Chinle flora. The second paper, entitled *Taphonomy of fossil plants in the Chinle Formation, Colorado Plateau, U.S.A.*, looks at the taphonomy of Chinle plants in a more general way. This paper classifies the Chinle flora by plant-bearing units (PBU's: depositional units which preserve fossil plants). The third paper, entitled *Incised-valley fills and the taphonomy of fossil plants: An example from the Upper Triassic Chinle Formation, Colorado Plateau, U.S.A.*, looks at the sedimentologic and taphonomic framework of a fully-terrestrial incised-valley fill sequence (the lower part of the Chinle Formation). This paper examines the Chinle flora from the perspective of regional to basin-wide aggradational events and discusses how the taphonomy of fossil plants can be affected by processes and conditions unique to these types of settings. These manuscripts are followed by the measured stratigraphic sections used in this project and the tables of the sedimentologic and taphonomic data from individual plant assemblages. The research done for this dissertation and summarized in these manuscripts was done totally by the author.
PRESENT STUDY

The methods of this study were presented in the previous introduction. The results and conclusions of this study are presented in the manuscripts appended to this dissertation. The following is a summary of the most important findings in these papers.

Exposures of the Monitor Butte Member of the Chinle Formation in Petrified Forest National Park have produced a significant proportion of the described fossil plants known from the Upper Triassic of western North America. These strata were deposited by aggradation in a paleovalley by lateral accretion in a high-sinuosity channel, which deposited the Newspaper sandstone body, and vertical accretion of its overbank sediments. Fossil plants are preserved in three types of deposits in the Newspaper channel and overbank system: 1) transported, coalified gymnosperm logs in basal lags in channel-fill/lateral accretion deposits, introduced into the channel by cut-bank erosion; 2) erect, casted, in situ horsetail trunks and horsetail leaf mats in crevasse splays that were buried and preserved by proximal overbank sedimentation; and 3) transported and in-place cycadeoid, cycad, fern, and other leaf material, and prostrate and erect trunks in litter layers in the paludal/distal splays that were preserved by distal overbank sedimentation.

Fossil plant assemblages in the Chinle Formation throughout the Colorado Plateau region were preserved in seven types of plant-bearing units (PBU's: defined as depositional units which contain fossil plants or plant parts). PBU's deposited in low-sinuosity channels contain silicified gymnosperm trunks preserved in dispersed assemblages in mid-channel facies, and concentrated assemblages in channel-margin facies. PBU's
deposited in high-sinuosity channels contain silicified, coalified, and cast
gymnosperm trunks, branches and stems, preserved in concentrated
assemblages in basal channel lags and on the upper parts of point bars.
PBU's deposited in abandoned channels contain in-place coalified
impressions of cycadeoid leaves and conifer shoots and in-place stems and
rhizomes of horsetails and lycophytes. PBU's deposited in crevasse splays
contain in-place cast stems of horsetails and associated litter layers. An
avulsion-related splay deposit in Petrified Forest National Park preserves in-
place silicified gymnosperm stumps and oriented parautochthonous silicified
gymnosperm logs. PBU's deposited in lacustrine deltas contain in-place
horsetail stems, and in-place and transported coalified impressions of
cycadeoid and fern leaves. PBU's deposited in paludal overbank areas
contain in-place and transported coalified compressions of cycadeoid, cycad
and fern leaves, and prostrate and erect gymnosperm trunks. PBU's in
paleosols contain in-place, silicified gymnosperm trunks, stumps, and roots.

The fossil plant assemblages of the Chinle Formation are concentrated
in the lower members of the formation in an incised valley system.
Depositional, hydrological, and near-surface geochemical conditions in the
incised-valley system were conducive to preservation of terrestrial organic
material, even though regional conditions were characterized by seasonal
precipitation and groundwater conditions. Fossil plant assemblages in fully
terrestrial incised valley-fills, like the lower part of the Chinle Formation, are
taphonomically biased toward plants that lived in riparian wetland
environments.
Appendix A: Sedimentology and plant taphonomy of a channel and overbank system, Upper Triassic Chinle Formation, Petrified Forest National Park

Abstract

A high-sinuosity stream and overbank system in the central part of Petrified Forest National Park preserves fossil plants in three types of deposits: 1) allochthonous logs in basal lags in a channel-fill/lateral accretion deposits; 2) autochthonous horsetail trunks and paraautochthonous horsetail leaves in a crevasse splays; and 3) paraautochthonous and autochthonous cycadaceous, fern and other types of leaves, and erect and prostrate trunks in a paludal/distal splays. Sedimentary structures in the channel and overbank deposits, and the taphonomy of the fossil plants indicate that the discharge regime and flooding in the fluvial channel was seasonally variable, suggesting that paleoclimate during deposition was characterized by seasonal precipitation. The preservation of in situ wetland plants, rare aquatic organisms, and the presence of paleosols indicative of saturated soil conditions in the overbank area suggest that water tables were high and that some areas had ponded water year-round, at least during the initial stages of deposition in the system.

Introduction

Fluvial and lacustrine deposits of the Chinle Formation in Petrified Forest National Park (Figure 1) have been the source for much of what is currently known about Early Mesozoic terrestrial ecosystems in western North America (Ash, 1987; Wing and Sues and others, 1992). Of the 41 described genera of fossil plants found in the Chinle, all but a few can be found within Petrified Forest National Park (Ash, 1972). Although the park
is named, and justly famous, for the permineralized gymnosperm logs that are found there, other fossil plants, including cycads, cycadeioids, ferns, horsetails, and others (Table 1), are locally abundant. One particular locality, near the central part of the park in an area known as the Tepees (Figure 1), has produced a significant number of the fossil plants that have been described from the Chinle. The fossil plants in this area were discovered in 1932 by workers improving the main road through the park (Ash, 1974). Plant fossils are present in greenish gray mudstones of the Monitor Butte Member (formerly the "lower" Petrified Forest Member; Dubiel and others, 1995) near the lowest part of the Chinle Formation in the park (Figure 2).

The site was first surveyed and collected by M.V. Walker, the first resident naturalist at Petrified Forest (Daugherty, 1941). The flora found at the Tepees was first described in detail by Daugherty (1941) and later refined and expanded by Ash (1972, 1974, 1991). However, even though the taxonomic composition of the flora at this important locality has been well described, the taphonomy of the fossil plants and the depositional environments of the plant-bearing units have not been addressed. This paper will summarize the previous work done on the Tepees locality, describe the sedimentology and depositional environments of the plant-bearing units and related strata at the Tepees, the taphonomy of the fossil plants preserved there, and then discuss paleoenvironmental and paleoclimatic implications of these interpretations.
Figure 1. Location of study area within Petrified Forest National Park, AZ
Table 1.
Fossil plants preserved in the crevasse splay and paludal/distal splay deposits (from Daugherty 1941; Ash, 1972, 1973, 1974, 1991)

<table>
<thead>
<tr>
<th>Group</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ferns</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Todites fragilis</em>¹</td>
</tr>
<tr>
<td></td>
<td><em>Cynepteris lasiophora</em>¹</td>
</tr>
<tr>
<td></td>
<td><em>Wingatea plumosa</em>¹</td>
</tr>
<tr>
<td></td>
<td><em>Phlebopteris smithii</em>²</td>
</tr>
<tr>
<td></td>
<td><em>Clathopteris walkerii</em>²</td>
</tr>
<tr>
<td></td>
<td><em>Cladophlebis daughertyi</em>¹</td>
</tr>
<tr>
<td></td>
<td><em>Cladophlebis sp. A</em>¹</td>
</tr>
<tr>
<td><strong>Cycadeoid</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Zamites powellii</em>³</td>
</tr>
<tr>
<td><strong>Cycad</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Aricycas paulae</em>²</td>
</tr>
<tr>
<td><strong>Horsetail</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Neocalamites virginiensis</em>⁴</td>
</tr>
<tr>
<td><strong>Lycophytes</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Isoetes circularis</em>²</td>
</tr>
<tr>
<td></td>
<td>*Lycopodies? sp.*¹</td>
</tr>
<tr>
<td><strong>Ginko</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Baiera arizonica</em>¹</td>
</tr>
<tr>
<td><strong>Conifers</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Samaropsis puerca</em>⁵</td>
</tr>
<tr>
<td></td>
<td><em>Araucarioxylon arizonicum</em>⁶</td>
</tr>
<tr>
<td><strong>Unassigned</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Sphenopteris arizonica</em>¹</td>
</tr>
<tr>
<td></td>
<td><em>Marcouia neuropteroides</em>¹</td>
</tr>
<tr>
<td></td>
<td><em>Carpolithus chinleana</em>⁵</td>
</tr>
</tbody>
</table>

1-rare; 2-common; 3-abundant; 4-abundant, trunks and leaves; 5-rare, seed; 6-wood
Figure 2. Composite stratigraphic section of the Chinle Formation in Petrified Forest National Park, AZ showing the position of the Newspaper Rock sandstone and the strata exposed in the Tepees area (after Dubiel and others, 1995).
Previous work

The plant-bearing strata at the Tepees area of Petrified Forest National Park were first described by Stagner (1941) as part of Daugherty's (1941) detailed survey of the Triassic flora of Arizona. Stagner (1941) described the plant-bearing units (his "leaf shale") as greenish to bluish gray mudstone and very fine micaceous sandstone. Most importantly, he noted that these units were laterally equivalent to, and interfinger with, a sandstone body, informally known as the Newspaper sandstone (Billingsley, 1985). This sandstone forms a prominent cliff, where Newspaper Rock (a spectacular petroglyph site) is located, and caps a low mesa in the central part of the park, north of the Tepees area (Figure 3). Stagner (1941) also noted that the greenish plant-bearing units pinch out to the south below a red mudstone unit and above a reddish to purplish gray bentonitic mudstone.

Ash (1972) revised Daugherty's (1941) descriptions of the fossil plants found at the Tepees locality, re-assigning some taxa to new genera or species, and rejecting others. Ash has also described two additional plants found at the Tepees, a fern (Ash, 1973) and a cycad (Ash, 1991).

Gottsfeld (1972) compared the megaplant, vertebrate, and invertebrate fossil assemblages of the Tepees and other localities at Petrified Forest National Park with pollen assemblages from the same stratigraphic units in an attempt to reconstruct the vegetation structure and paleoecology. He recognized three "communities": 1) a floodplain swamp community vegetated by cycadophytes and ferns and inhabited by metoposaurs, phytosaurs, lungfish, and semionotid fish; 2) a lowland, closed-canopy forest vegetated by Araucarioxylon trees and understory of ferns; and 3) an upland community
Figure 3. Location of measured sections in the Newspaper Rock and Tepees areas of Petrified Forest National Park. 1650 meter topographic contour line and main park road shown for location. Line of section A-A' for Figure 5.
vegetated by diverse gymnosperms and inhabited by dinosaurs and pseudosuchians.

Middleton and others (1985), Blakey and Middleton (1986), and Kraus and Bown (1986) described paleosols and inclined strata associated with large-scale scour surfaces in the Tepees area. They interpreted dipping pale red and gray mudstones (laterally equivalent to Stagner's, 1941, "leaf shale") within the scour fills as aggrading levee deposits capped by immature paleosols, and noted that the dip directions in these strata are 90° to paleocurrent directions taken from the laterally equivalent sandstone body. Kraus and Middleton (1987), in a brief review of fluvial deposition in the lower Chinle, described the Newspaper sandstone as having been deposited by a sandy, low-sinuosity stream system that had a variable discharge regime and sediment supply.

Hasiotis and Dubiel (1993) discussed trace fossils in the Tepees strata. They described three distinct trace fossil assemblages, each found in a different interpreted depositional environment. Horizontal burrows, trails, and resting traces were found in submerged point-bar, levee, and splay environments, whereas vertical burrows and distinct crawling traces were found in exposed portions of these environments. Scoyenia, a type of insect larva burrow, was found in the third sedimentary facies, saturated floodplain paleosols.

Depositional environments

The Tepees/Newspaper Rock fluvial deposits were deposited in five different subenvironments: 1) channel fill/point bars; 2) levees; 3) crevasse splays; 4) paludal/distal splays; and 5) distal alluvial paleosols. These
deposits fill an incised paleovalley defined by one of the major scour surfaces in the Tepees area described by Middleton and others (1985), Blakey and Middleton (1986), and Kraus and Bown (1986). The following section describes the sedimentary facies and interpreted depositional environment each of these types of deposits.

*Channel Fill/Lateral Accretion Deposits*

The plant-bearing mudstones at the Tepees are laterally equivalent to and interfinger with the Newspaper sandstone (Stagner, 1941), here described as the channel-fill/lateral accretion deposits in the Newspaper fluvial system. This sandstone, 10 m thick where best developed, is a yellowish brown, fine- to medium-grained, well-sorted sandstone with thin mud-clast conglomerate interbeds. The lower parts of the channel-fill facies are characterized by scour surfaces and large-scale trough cross-bed sets (1-2 m thick) capped by thin (0.3-0.5 m thick) sets of small-scale trough cross beds and plane parallel lamination (Figure 4). The upper part of the facies has thick (1-3 m) sets of small-scale trough cross beds and climbing-ripple cross-laminae capped by plane parallel laminae that exhibit primary current lineation. Large-scale, inclined (15-20°) surfaces in the sandstone body are the bounding surfaces between individual lateral-accretion elements (Figures 5 and 6). The upper parts of these lateral-accretion elements are exposed in plan view on the top of the low mesa between Newspaper Rock and the Tepees, reflecting the original scroll-bar topography. There are two distinct groups of lateral accretion sets, one directly to the north of the Tepees area, in which the lateral accretion surfaces dip to the north, and one around and to the east of Newspaper Rock, in which the surfaces dip to the west (Figure 7).
Figure 4. Measured stratigraphic sections in the Newspaper Rock and Tepees area of Petrified Forest National Park, AZ. Numbers at top of columns correspond to section numbers on Figure 3.
Figure 5. Panel diagram of fluvial and overbank deposits in the Newspaper Rock and Tepees area. Line of section A-A' from Figure 3. Section numbers refer to columns in Figure 4.
Figure 6. Exhumed lateral accretion sets mapped in the Newspaper Rock sandstone. TP: Tepees area, NR: Newspaper Rock petroglyph site.
Figure 7. Rose diagrams of paleocurrent directions and log orientations.

EXPLANATION

CH = channel-fill/lateral accretion deposits
L = levee deposits
C = crevasse deposits

50 = total # of measurements

% of measurements

lateral accretion sets with dip direction

channel lag logs
Paleocurrent directions measured from small-scale trough cross beds and primary current lineation the channel-fill/lateral accretion deposits are to the west-southwest in the area directly north of the Tepees area, and to the north in the area around Newspaper Rock (Figure 7). Coalified trunks, branches, and large stems are present as a basal lag (Figure 8) in the channel deposits.

Interpretation. - The channel-fill/lateral accretion deposits which makes up the Newspaper multilateral sandstone body was deposited by point-bar migration and channel aggradation in a high-sinuosity stream. The large-scale trough cross beds and scour-fills in lower parts of the Newspaper Rock sandstone represent deposition by large 3D ripples in the thalweg of the channel. Mud-clast conglomerate beds were produced by erosion and scouring of underlying mudstones and contemporaneous floodplain sediments. Small-scale trough cross beds and climbing-ripple cross-lamination in the upper parts of the lateral accretion elements were formed by rapid deposition of suspension load and aggradation of 3D ripples during the waning flow of bankfull and higher discharges. Plane parallel lamination was formed during upper flow regime conditions as flood stages continued to wane. The two distinct sets of lateral accretion beds were formed by the migration of two separate point bars on the insides of meanders in the Newspaper channel -- the northern set was probably formed by the point bar (which migrated to the west) downstream from the one that formed the southern set (which migrated to the north). The dip directions of both sets of lateral accretion sets indicate that the Newspaper channel tended to migrate away from the Tepees area during meander migration, aggradation, and the infilling of the incised paleovalley scour.
Figure 8. Coalified and sand-casted logs preserved in the base of the channel/lateral accretion facies of the newspaper Rock sandstone. Knife is 9 cm long.
The channel-fill/lateral accretion deposits that make up the Newspaper sandstone are similar to high-sinuosity point bar and channel deposits described by McCabe (1978) from the Carboniferous of New Brunswick and Nova Scotia, Smith (1987) from the Permian of South Africa, Puigdefabregas (1973) and Friend and others (1979) from the Miocene in northern Spain, and Edwards and others (1983) from the Permian in Texas.

*Levee Deposits*

The levee deposits are laterally equivalent to the upper portions of the channel-fill/lateral accretion deposits, and are composed of yellowish brown to grayish brown, very fine-grained sandstone and siltstone. These deposits crop out poorly and are usually exposed only beneath some of the crevasse sandstone units described below. Sedimentary structures in these deposits include small-scale trough cross-bed sets and climbing-ripple cross-lamination. The levee deposits are characterized by irregular, stacked, fining-upward units. The basal portions of each of these units are very fine-grained, cross-bedded sandstone, grade up to very fine-grained and ripple cross-laminated sandstone, and are capped by rooted siltstone (Figure 9). The bounding surfaces between these units dip (3-5°) both toward and away from the channel-fill/lateral accretion deposits. The tops of these units are often rippled and mud-cracked, and have small, erosional beach faces. Paleocurrent directions measured from the levee deposits are to the west (Figure 7).

*Interpretation.* - The levee deposits were deposited during waning flow of overbank floods. Small-scale trough beds and climbing-ripple cross-lamination represent rapid deposition during suspension load fall-out and
Figure 9. Outcrop of area of interfingering of channel-fill/lateral accretion facies, levee facies, and paludal/distal splay facies, all overlain by the alluvial paleosol facies.
aggradation of 3D ripples during the waning stages of overbank floods. Rippled surfaces formed during lower stages of floods, and mudcracks and shoreline features formed during subsequent subaerial exposure.

**Crevasse Splay Deposits**

The crevasse splay deposits consist of grayish brown to greenish gray, very fine- to fine-grained sandstone, siltstone, and mudstone. These deposits are characterized by 10 to 15 thin (< 1m) fining-upward units (Figure 10). Each splay package consists of very fine- to fine-grained, ripple cross-laminated sandstone overlain by laminated or rootworked siltstone and mudstone. The uppermost units are reddish brown and rooted at the top, and have small (2-3 mm diameter) iron nodules. Some coarser-grained (very fine and fine sandstone) and better-sorted portions of the splay units are calcite cemented, and crop out as distinct ledges in the surrounding siltstone- and mudstone-dominated badlands in the Tepees area. Some of these distinctive splay units can be traced for several kilometers; one prominent unit caps the badlands, known as the Haystacks, to the west of the Tepees and south of Newspaper Rock. The splay units are generally coarser grained (sandstone) where they interfinger with channel-fill/lateral accretion and levee deposits, and finer (siltstone and mudstone) where they grade into paludal/distal splay deposits. There are several small, channel-shaped scours in the upper part of the crevasse splay deposits (Figure 4), filled with either inclined siltstone and mudstone beds indistinguishable from those in the splays, or very fine- to fine-grained, cross-bedded sandstone. Paleocurrent directions measured in the crevasse splay deposits are to the south (Figure 7). *Neocalamites* leaves and trunks are the dominant plant fossil preserved in
Figure 10. Outcrop of crevasse splay facies in the Tepees area showing stacked fining-upward units. The crevasse splay facies is capped by alluvial paleosol facies. Person for scale.
this facies (Figure 11). Abundant vertical burrows and crawling traces occur in the sandy portions of the splay deposits (Hasiotis and Dubiel, 1993).

Interpretation.- The crevasse splay deposits were deposited, during repeated overbank floods, on the proximal floodplain of the stream that deposited the Newspaper sandstone. The small channels in the upper part of the splay deposits are interpreted as chute channels cut into the splays during overbank flooding and filled during subsequent overbank sedimentation. Each of the fining-upward units in the crevasse splay deposits represents deposition during a single overbank flooding event. The pronounced vertical stacking of the splay units can be attributed to: 1) aggradation of the Newspaper channel/overbank system and progressive infilling of the incised valley and 2) local accommodation space generation by compaction of underlying mudstones of the paludal/distal splays. Between flood events, the surfaces of the splays were subaerially exposed, and were vegetated and pedogenically altered. The paleosols at these surfaces are weakly developed, characterized by only slight color mottling and horizonation and the accumulation of small ferrous glaebules. These features reflect the development of relatively immature soils, and indicate that these paleosols should be classified as Protosols (sensu Mack and others, 1993). The paleosols in the crevasse splay deposits were only weakly developed because of a relatively high sedimentation rate -- pedogenesis at a splay surface was arrested by burial during the next splay event. The stacked splay/Protosol sequence at the Tepees is similar to stacked clastic-swamp paleosols described by Demko and Gastaldo (1992) in Pennsylvanian rocks in the Warrior Basin.
Figure 11. *Neocalamites* fossils from crevasse-splay deposits. A, erect trunk buried and cast by sandstone. B, leaf mat on bedding plane.
Paludal/Distal Splay Deposits

The paludal/distal splay deposits are equivalent to Stagner's (1941) "leaf shale" unit. They interfinger with and is covered by the crevasse splay deposits (Figure 4). These deposits are composed of olive gray to greenish gray mudstone, siltstone, and very fine-grained sandstone. They, like the crevasse splay deposits, are characterized by thin (<1 m thick) fining-upward units with laminated and micro-cross-laminated, very fine-grained sandstone and siltstone at the base and laminated to rootworked mudstone at the top of each unit. Abundant coalified and/or permineralized leaves, seeds, stems, trunks, and roots are preserved in the paludal/distal splays (Daugherty, 1941; Ash, 1972, 1973, 1991). Rare conchostrachans, a single crayfish specimen (Miller and Ash, 1988), and several unidentified insect fossils (Robert Smith, personal communication) have also been reported from these deposits.

Interpretation.- The paludal/distal splay deposits were deposited in a low-lying area on the floodplain of the stream that deposited the Newspaper sandstone. These deposits represent the finer-grained, distal margins of crevasse splays. The fining-upward units in the paludal/distal splay deposits can be traced directly into coarser-grained equivalent units in the crevasse splay deposits. However, the upper parts of these fining-upward units in the paludal deposits show no evidence of pedogenic alteration, although preserved in situ plants (see taphonomy section below) indicate that the sediment surfaces were vegetated. The lack of pedogenic alteration features and the presence of conchostrachans, although rare, suggest that these units were deposited in an area with a high water table and, at least at sometimes, standing water at the surface. The drab olive gray to greenish gray colors,
preservation of organic material, and pyritic permineralization of wood (see below), indicate a water-saturated, reducing soil environment. Because the paludal/distal splay deposits are present only in the lowest parts of the sequence and is overlain by splay units with paleosols (Figure 5), these conditions of total soil saturation and ponded surface water must have existed only during the initial stages of floodplain aggradation and infilling of the paleovalley.

*Distal Overbank Paleosols*

The distal overbank paleosols consists of brownish red and light gray mottled smectitic mudstone and siltstone. They are characterized by a massive to rootworked texture, slickensides, blocky to flaky fracture, calcareous nodules (3-5 cm diameter), and the trace fossil *Scoyenicia*. Color mottling in this facies is expressed as light gray gley spots and halos, usually around rootlets. This facies is present in the Tepees area as a distinct reddish band of mudstone 1-4 m thick (Figure 12) above the sandstone beds of the levee and lateral accretion deposits, and the olive gray-and reddish brown-striped mudstones and siltstones of the crevasse splay and paludal deposits in the northern part of the Tepees area, and above purple mudstones below the scour surface to the south (Figure 5).

*Interpretation.* The distal overbank paleosols represents the formation of a mature soil on the uppermost crevasse splay units from the Newspaper channel and on older alluvial material below the incised paleovalley scour surface. This paleosol was more strongly developed, and represents a longer time of pedogenesis, than any of the protosols from the underlying splay deposits. The burrowed and rootworked texture indicates
Figure 12. Outcrop of alluvial paleosol facies in the Tepees area showing position of Bt and A-E horizons. Person for scale.
complete bioturbation, both by invertebrates and rooting. Blocky and flaky fracture and slickensides in the paleosol are the result of translocation of clay within the soil profile, and the formation of peds and argillans in an incipient Bt horizon (Retallack, 1990). Calcareous nodules were formed by the precipitation of micritic calcium carbonate in a Bk horizon due to root transpiration of vadose water (Goudie, 1983). This paleosol would be termed an argillic Calcisol in the classification of Mack and others (1993), based on the presence of pedogenic carbonate nodules and a horizon with translocated clay. The paleosol was able to develop at this point in the depositional sequence because of a decrease in floodplain sedimentation rate due to the migration of the Newspaper channel away from the Tepees area.

Plant Taphonomy

Plant megafossils are abundant in channel-fill/lateral accretion, crevasse splay, and paludal/distal splay deposits in the Newspaper Rock/Tepees area. The following section will describe the taphonomy of the fossil plants preserved in these deposits. This information is summarized in Table 2.

Channel Fill/Lateral Accretion

The plant fossils in channel-fill/lateral accretion deposits of the Newspaper sandstone include coalified trunks and stems preserved as a basal lag (Figure 8). These xylic elements are present in the lowest parts of the channel-fill sequence, at the scour surface at the base of the sandstone. The trunks are abundant, although patchy, reaching densities of 3-5 trunks/m² in log jams that cover 4-10 m². These small jams are present in scoured depressions in the underlying mudstones. About half of these trunks
Table 2. Summary of taphonomy of fossil plants at the Tepees locality, Petrified Forest National Park

**Sedimentologic Data**

<table>
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<th>Parameter</th>
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<th>10m</th>
<th>100m</th>
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</tr>
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<td>Lithology</td>
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</tr>
<tr>
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<tr>
<td>of plant parts</td>
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**Taphonomic Data**

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<tr>
<td># identifiable parts</td>
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<tr>
<td>Spatial density (parts/m²)</td>
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<tr>
<td>Size of remains (cm)</td>
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</tr>
<tr>
<td>Organ dominance (stem/leaf, etc.)</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Transport</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Diversity (# dominants)</td>
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**Deposits**

<table>
<thead>
<tr>
<th>Type</th>
<th>Channel-fill/lateral accretion deposits</th>
<th>Crevasse splay deposits</th>
<th>Paludal/distal splay deposits</th>
</tr>
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</table>
are hollow and cast by sandstone. These trunks and stems range in size between 0.05-0.5 m in diameter and 0.5-2 m in length. The trunks have no lateral branches or roots preserved; however, some individual specimens with forked trunks are present. Hollow, casted trunks are circular to oval in cross section, whereas solid trunks are flattened. All of these fossils are degraded, abraded, and poorly preserved. They are not assignable to any known genus; however, the hollowed trunks broadly resemble those of *Neocalamites*, whereas the flattened trunks are probably those of gymnosperms. The trunks are oriented with paleocurrents in the Newspaper sandstone (Figure 7).

**Interpretation.** - The coalified and cast trunks present at the base of the channel-fill/lateral accretion deposits are allochthonous xylic elements that were buried after transport as bedload in the Newspaper channel. They were most likely part of the arborescent riparian streamside vegetation and were introduced into the channel environment by cut-bank erosion during channel migration and floodplain erosion during overbank flooding. The trunks were trapped in small log jams in deeper pools near the thalweg of the channel, oriented by the prevailing stream currents, and subsequently buried by large 3D ripples which filled in the scours. Poor preservation of this assemblage resulted from degradation and abrasion in the channel environment prior to burial, and also by burial in relatively coarse sediment.

**Crevasse Splay**

Trunks and leaves from the horsetail *Neocalamites* are preserved in the crevasse splay deposits. Trunks, 0.2-0.3 m wide and < 1 m high (preserved height, obviously eroded at outcrop), are cast by very fine-grained sandstone and preserved upright and in situ (Figure 11a). They are buried by 2 or 3 of
the individual splay units. These trunks are in clumps of 2-3 closely spaced trunks separated by 5-10 m along the outcrop. Leaves are preserved as compression fossils in the finer-grained upper portions of the splay units. They form mats, usually only one leaf thick, that cover single bedding planes (Figure 11b) and have a densities of hundreds of leaves per square meter. Neither the trunks nor leaves were hydrodynamically oriented prior to burial.

Interpretation.- Neocalamites trunks and leaves preserved in the crevasse splay deposits were in situ elements of the proximal overbank vegetation buried by sedimentation during overbank flood events. The Neocalamites plants, however, were not killed by these burial events, at least not by the sediments that buried the bases of the trunks. As Demko and Gastaldo (1992) and Gastaldo (1992) pointed out in studies of Pennsylvanian calamiteans, these types of plants were able to withstand repeated burial of the lower parts of the trunk, and could continue life processes after the growth of new adventitious rooting structures. After the eventual death of the plants, the the hollowed pith cavities in the buried portions of the trunks were filled by subsequent overbank sedimentation, forming autochthonous pith casts.

The Neocalamites leaf mats represent paraautochthonous litter layers, accumulated by normal abcission from their parent plants and preserved by initial sedimentation during the crevasse events.

**Paludal/Distal Splay**

Compressions of pinnate leaves from the cycadeoid Zamites powelli are the dominant plant fossils preserved in the paludal/distal splay deposits. Compressions of pinnate leaves and individual pinnae from the cycad Aricycas paulae, attached pinnate leaves and rachi of the fern Phlebopteris smithii, and
leafy shoots from the protognetalean? *Dinophyton spinosus* are locally abundant. Erect stumps (0.3-0.5 m high, 0.2-0.4 m diameter) and flattened and mudstone-cast prostrate logs (0.5-1.5 m long, 0.2-0.4 m diameter) are common. Some are coalified (Figure 13), others pyritized, and a few are silicified. The stumps and logs are poorly preserved, and cannot be assigned to any genus; however, they resemble better-preserved gymnosperm trunks from other localities. Other types of plant fossils found in these deposits include compressions of leaves from other ferns, fern-like plants, and unassignable taxa, conifer seeds, and lycophyte stem and leaf material (Table 1); however, they are rare and some are known and described only from single and/or fragmentary specimens (Ash, 1972).

*Zamites, Phlebopteris,* and *Aricycas* leaves are preserved as compressions of abcised fronds 10-40 cm long and 10-15 cm wide parallel to bedding planes. *Dinophyton* shoots are preserved as compressions of single shoots 10-15 cm long and 3-8 cm wide, parallel to bedding planes. However, a few *Phlebopteris* specimens are preserved as multiple leaves attached to stems that cross-cut bedding planes at low angles (5-10°), and probably represent whole, *in situ* plants. The abcised shoots and pinnate leaves are preserved on the uppermost bedding planes of the finer-grained (mudstone), upper parts of the fining-upward units in the paludal/distal splay deposits, whereas the multiple, attached *Phlebopteris* leaves are preserved in the lowest, coarser-grained (silty mudstone) parts of these units. Erect and prostrate trunk material is preserved at the boundaries between the fining-upward units. All of the foliar material is very well preserved, including the cuticle. The only damage observable is shriveling of the basal pinnae in some
Figure 13. Coalified erect stump from paludal/distal splay facies. Scale is marked in 10 cm increments.
specimens of *Aricycas paulae*, attributed by Ash (1991) to senescence before abscission.

**Interpretation.** The fossil plants preserved in the paludal/distal splay deposits represent autochthonous and paraautochthonous elements of herbaceous and arborescent wetland vegetation. Abundant cycadeioids and ferns and subdominant cycads, protognetaleans?, conifers, and other plants formed the standing vegetation and surface litter in an overbank wetland area in the proximal floodplain of the Newspaper channel. These plants, and the surface litter layer they generated, were repeatedly buried by sedimentation during overbank flood events. The surface litter layer, consisting mostly of abscised cycadeiod leaves, was preserved by initial suspension load fall-out and was not transported. The floodplain surface was not scoured by these floods. Whole fern plants, with delicate fronds still attached, and the bases of trees were buried *in situ*. The high water table in this area, including some standing water, created anaerobic, reducing conditions in the soil, arresting decay, and allowing preservation of the original plant material, including cuticle. Buried xylic material was permineralized by pyrite and silica, and the remaining organic matter, excluding leaf cuticle, was coalified after burial.

**Discussion**

The plant fossil assemblages in the Newspaper sandstone and the strata at the Tepees were preserved in facies deposited by a high-sinuosity channel and overbank system that was actively aggrading and filling an incised paleovalley. Using values of point-bar width and depth from outcrops and estimates of meander amplitude and wavelength from aerial
photographs, values of channel width and depth and mean annual discharge ($Q_m$) were estimated using empirical formulas (Table 3). These calculations indicate that the Newspaper channel had a bankfull width of 100-120 m, a bankfull depth of 6.5-7.5 m, and a $Q_m$ of 947-1374 m$^3$/s. A sinuosity ($P$) of 1.7-1.94 was estimated from the traces of lateral accretion sets and paleocurrent measurements (Figure 7). The sedimentary structures within individual lateral accretion elements, which make up the bulk of the Newspaper sandstone body, suggest that they were deposited during single flood events. This preferential preservation of flood deposits in the point-bar sequences, and the continuity of bounding surfaces between lateral accretion elements down to the base of the channel, are interpreted as evidence of a highly variable discharge regime (Puigdefabregas and Van Vleit, 1978).

The overbank deposits in this system were also dominated by flood sedimentation. The levee, crevasse splay, and paludal/distal splay deposits all consist of fining-upward units attributable to sedimentation during overbank flood events. However, weakly developed paleosols, drab greenish gray coloration, and rare fossils of aquatic organisms in the crevasse splay and paludal/distal splay facies suggest a perennially high water table, with some areas of ponded surface water between flood events.

The fossil plants preserved in the Newspaper channel were transported to some degree; however, plants preserved in the overbank facies were preserved in situ or very close to their growth sites. The trunks that make up the small log jams in the basal lag in the channel were probably introduced into the channel by cut-bank erosion, transported, trapped in deep pools, and buried by bedform migration. These types of assemblages were probably
Table 3. Paleohydraulic parameters of the Newspaper channel.

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<tr>
<th>Measured parameters</th>
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<td>Db (channel bankfull mean depth)</td>
<td>6.5-7.5 m</td>
<td>thickness of lateral accretion set</td>
</tr>
<tr>
<td>Wb (channel bankfull width)</td>
<td>100-120 m</td>
<td>1.5 X width of point bar (1)</td>
</tr>
<tr>
<td>Re (radius of curvature of meander)</td>
<td>840-1000 m</td>
<td>exhumed lateral accretion sets</td>
</tr>
<tr>
<td>P (sinuosity)</td>
<td>1.7-1.94</td>
<td>exhumed lateral accretion sets and paleocurrent vectors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculated parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Lm (meander wavelength)</td>
<td>3377-4006 m</td>
<td>$L_m = 4.60R_c^{0.98}$ (2)</td>
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<tr>
<td>Qm (mean annual discharge)</td>
<td>1043-1374 m$^3$/s</td>
<td>$Q_m = 0.0025R_c^{1.58}$ (3)</td>
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<td></td>
<td>947 m$^3$/s</td>
<td>$Q_m = 0.000017L_{max}^{2.15}$ (4)</td>
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(1) Allen (1966)  
(2) Leopold and Wolman (1960)  
(3) Williams (1984)  
(4) Williams (1984) modification of Carlson (1965)
derived from local, arborescent, riparian vegetation that grew along the outside banks of meanders (Spicer, 1989, 1991). The bases of erect trunks of the horsetail *Neocalamites virginiensis* preserved in the crevasse splay deposits were buried in place, and the plants continued life processes afterwards. Mats of abcised horsetail leaves, which formed surface litter layers around these trunks, were preserved near their parent plants. The *in situ* and parautochthonous horsetail fossils form a monospecific assemblage in the crevasse splay deposits where they interfingers with the paludal/distal splay deposits. These stands of horsetails must have been the fringing vegetation around the paludal and ponded water areas on the floodplain proximal to the channel, uniquely adapted to living in an area of high sedimentation rate.

Fossil plants preserved in the paludal/distal splay deposits were also preserved in or near their growth sites. Erect trunks and whole fern plants were preserved *in situ*, whereas abcised cycadeoid and cycad leaves and pinnae and prostrate logs were parautochthonous. Ash (1975, 1991) has suggested that both the cycadeiod *Zamites powelli* and the cycad *Aricycas paulae* were deciduous based on slight swellings and clean breaks at the basal ends of their petioles. No identifiable, *in situ*, cycad or cycadeiod trunks have been found in the paludal/distal splay deposits, and only two (Lyssonylon; Daugherty, 1941, and Charmogoria; Ash, 1985) have been described from the Chinle, neither found in the Tepees area. However, some of the erect, *in situ* and prostrate, poorly preserved, unidentifiable, coalified trunks from the paludal/distal splay deposits could have been parent stems or trunks to these plants. In any case, the abcised cycadeoid, cycad, and other
types of leaves were preserved as litter layers at the tops of the fining-upward sedimentation units in the paludal/distal splay deposits along with erect and prostrate trunks and autochthonous ferns. The leaves in these litter layers are all very well preserved, the only damage is the slight wrinkling of the basal pinnae on some Aricycas specimens noted by Ash (1991). This suggests that the leaves in single litter layers were dehisced synchronously rather than asynchronously (year-round) (Spicer, 1989). If the abcised leaves and prostrate trunks were transported at all, it is likely that they were transported only short distances from nearby levee or proximal splay areas. Gastaldo and others (1987) have pointed out that flood events in overbank wetland areas are usually not characterized by strong currents that transport the local litter. Instead, the water table gradually rises, saturating the litter layer before peak flood flow conditions. During peak flow and waning stages, the saturated litter layer and in-place plants actually enhance sedimentation by trapping fine-grained suspension load. The preservation of litter layers dominated by well-preserved, synchronously abcised leaves at the base of flood "event beds" suggests that the litter layers were formed a short time (< 1 yr) before the flood event, before the litter had a chance to decay, degrade, or have been subject to detritivory. This could have been due to synchronous leaf fall during dry periods before the flood events.

Evidence of both seasonal discharge regime in the Newspaper channel and synchronous deciduousness of the floodplain vegetation are consistent with the monsoonal paleoclimatic regime during Chinle time postulated by Dubiel (1994) and Dubiel and others (1991). In this respect, the Newspaper channel was similar to modern streams in the Kamala-Balan river system on
the Indo-Gangetic plains, characterized by high-sinuosity streams carrying fine-grained sediment in a highly seasonal discharge regime (Sinha and Friend, 1994).

The fossil plant-bearing facies in the Newspaper channel and overbank system are located at the base of a paleovalley fill (Figure 5). This paleovalley was formed by landscape degradation and incision of the Newspaper channel into underlying fluvial channel and overbank sediments due to a base-level fall. Relief on the landscape before aggradation and filling of the paleovalley was at least 12-13 m, based on the thickness of the fill. During the subsequent base-level rise, landscape aggradation, and deposition of the Newspaper channel and overbank sediments, sedimentation was confined to the paleovalley (Figure 14). Because the fluvial system was confined to the paleovalley, overbank sedimentation rates were higher than if the fluvial system were unconfined on a low-relief landscape. At the same time, during the initial stages of aggradation in the paleovalley, water table levels were high in the overbank areas, creating wetlands and some areas of ponded surface water. These conditions of high sedimentation rate and saturated soil conditions allowed burial of the overbank vegetation below the water table, increasing its preservation potential. As the paleovalley filled and the Newspaper channel migrated away from the Tepees area, the system became less confined--overbank sedimentation rates lessened, the water table fell, and well-developed soils formed, decreasing the preservation potential of fossil plants. The concentration of fossil plants in facies associated with the initial filling of local accommodation space, like the Newspaper Rock/Tepees locality, is a common theme in the Chinle Formation.
Figure 14. Paleogeographic reconstruction of the Newspaper Rock/Tepees area. A, initial stages of infill of paleovalley. B, lateral migration of point bars and splay deposition during latter stages of paleovalley infill.
Summary

Exposures of the Monitor Butte Member of the Chinle Formation around the Tepees and Newspaper Rock areas of Petrified Forest National Park have produced a significant proportion of the described fossil plants known from the Upper Triassic of western North America. These strata were deposited by aggradation in a paleovalley by lateral accretion in a high-
sinusosity channel, which deposited the Newspaper sandstone body, and vertical accretion of its overbank sediments. Five types of deposits recognized in the Newspaper channel and overbank system: 1) channel-fill/lateral accretion deposits; 2) levee deposits; 3) crevasse splay deposits; 4) paludal/distal splay deposits; and 5) distal overbank paleosols. Exposures of the tops and cross sections through lateral accretion elements from the Newspaper channel indicate that the sandbody is made up of two major sets of lateral accretion elements deposited by two point bars—one north of the Tepees area, deposited by a segment of the channel that flowed to the west and migrated to the north, and one northwest of the Tepees, deposited by a segment of the channel that flowed to the north and migrated to the west (Figure 14). Each of the lateral accretion elements in these sets was deposited by a flood event. Three types of plant-bearing units are present in the Newspaper channel and overbank system: 1) allochthonous, coalified gymnosperm logs in the basal lags in the channel-fill/lateral accretion facies, introduced into the channel by cut-bank erosion during channel migration; 2) erect, casted, in situ horsetail trunks and horsetail leaf mats in the crevasse splay facies buried and preserved by overbank sedimentation proximal to the channel; and 3) paraautochthonous and autochthonous
cycadeiod, cycad, fern, and other leaf material, and prostrate and erect trunks in litter layers in the paludal/distal splay facies preserved by overbank sedimentation distal to the channel. Preferential preservation of flood deposits in the channel system and litter layers with uniformly well-preserved, abcised, deciduous leaves in the overbank area indicate that the discharge regime and flooding in the¬the Newspaper channel was seasonally variable, suggesting that paleoclimate during deposition was characterized by seasonal precipitation. The presence of in situ wetland plants, rare aquatic organisms, and paleosols indicative of saturated soil conditions in the overbank area, however, suggests that that water tables were high and some areas had ponded water year-round, at least during the intial stages of deposition in the system.

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Appendix B: Taphonomy of fossil plants in the Upper Triassic Chinle Formation, Colorado Plateau, U.S.A.

Abstract

Fossil plants in the Upper Triassic Chinle Formation are preserved in low-sinuosity channel, high-sinuosity channel, abandoned channel, crevasse splay, lacustrine delta, paludal overbank, and paleosol deposits. Fossil plant assemblages in plant-bearing units in these deposits are classified into seven taphofacies based on these depositional environments or subenvironments. The taphofacies contain autochthonous, paraautochthnous, and allochthonous elements of the Chinle flora, including cycadeoid, cycad, and fern leaves, horsetail stems and leaves, gymnosperm stumps, trunks, roots, and shoots, protognetalean? shoots and samaras, and reputed proto-angiosperm leaves. Taphonomic characteristics of these assemblages, and of individual plant fossils within them, indicate that most plant fossils have either not been transported far from their growth sites or are preserved in situ. Census of paraautochthonous and autochthonous elements in these taphofacies indicates that wetland areas were dominated by cycadeoids and ferns, marginal aquatic areas were dominated by horsetails, and drier areas were dominated by arborescent gymnosperms. Litter layers containing deciduous leaves all in the same state of preservation suggests some degree of seasonality in the climate, although the entire assemblage is taphonomically biased towards preservation in wet depositional environments.

Introduction

The fossil plant assemblage from the Upper Triassic Chinle Formation in the Colorado Plateau region (Figure 1) is the best described and most
Figure 1. Map of study area showing locations where plant-bearing units were described. Inset, locations within Petrified Forest National Park, AZ. PF, Petrified Forest National Park; MV, Monument Valley; WC, White Canyon area; BI, Big Indian Valley; SR, San Rafael Swell; CR, Capitol Reef National Park; LL, Long Logs; TP, Tepees area; NR, Newspaper Rock; BF, Black Forest.
extensive Triassic flora from North America (Ash, 1986a, 1989a; Dobruskina, 1994), and is an important component in paleoenvironmental interpretations of western North America and global paleoclimatic interpretations for the Early Mesozoic (Dubiel and others, 1991; Dubiel, 1994). Although the taxonomy and systematics of this flora have been well described (see summary below), the taphonomy of the fossil plants, including the sedimentology and depositional environments of the plant-bearing facies, has not been addressed. Further evaluation, refinement, or revision of previous paleoenvironmental and paleoclimatic interpretations of the Chinle Formation require that the Chinle flora be placed within a sedimentological and taphonomic framework so that it may be interpreted within the context of depositional environments on the Late Triassic landscape. The taphonomy of the fossil plants, and the distribution of plant taphofacies in space and time, also provide additional information on the depositional and paleoclimatic setting. This paper will describe the taphonomy of the fossils plants and the depositional environments of the plant taphofacies in the Chinle Formation and discuss their paleoenvironmental and paleoclimatic significance.

**Chinle flora**

the *Eoginkgoites* zone contained within the lower part of the Chinle in the Shinarump and Temple Mountain Members, and the *Dinophyton* zone in the overlying Monitor Butte Member and the lower part of the Petrified Forest Member [note: recent work in Petrified Forest National Park suggests that the "lower Petrified Forest Member" is stratigraphically equivalent to the Monitor Butte Member (Dubiel and others, 1995)] (Figure 2). Plant fossils are rare in the upper part of the Chinle (the Owl Rock, Rock Point, and Church Rock Members), but those found there are distinctive enough that Ash (1987b) has assigned them to a third floral zone, the *Sanmiguelia* zone. The age of the Chinle flora, based on both plant macro- and microfossil correlations and biostratigraphy, is late Carnian- early Norian (Ash, 1980; Dobruskina, 1985; Litwin, 1991), although recent isotopic dating of an ash fall deposit in the Petrified Forest Member yielded an absolute date of 207±4 Ma (Riggs and others, 1994), close to the Triassic-Jurassic boundary.

**Tectonic, climatic and depositional setting**

The Chinle Formation was deposited in a broad, fully terrestrial, cratonic basin on the western margin of Pangaea, interpreted by Lawton (1994) as a back-bulge basin created by subsidence due to viscous flow in the mantle associated with the subduction of the Farallon plate. During the Late Triassic, sediments were deposited extensively over western North America (Dubiel, 1994) and the Colorado Plateau/Four Corners region was a regional depocenter (Blakey, 1989). In this area, the Chinle is more than 500 m thick (Dubiel, 1989b). Sediments deposited in the Chinle basin came from source areas in the remnants of the ancestral Rocky Mountains to the east of the basin (Blakey and Gubitosa, 1983; Dubiel, 1994), uplifted Paleozoic rocks
Figure 2. Stratigraphic column of Chinle Formation showing position of plant-bearing units. Abbreviations as in Figure 1.
and possible arc-related volcanic rocks to the south (Stewart and others, 1972, 1986), and also as wind-transported volcanic ash from contemporaneous arc-related eruptions to the southwest and west of the basin (Stewart and others, 1986; Riggs and others, 1994).

Paleogeographic reconstructions of Pangaea, based on paleomagnetic data, place the Chinle basin in the tropical belt 5°-10° north of the Late Triassic equator (Witte and Kent, 1989; Bazard and Butler, 1991). Sedimentological evidence, including vertic paleosols and cyclic lacustrine deposits, and paleontological evidence, including crayfish and lungfish ichnofossils, growth bands in unionid bivalves, and taphonomic characteristics of some vertebrate assemblages indicating desiccation and trampling prior to burial, suggest that the paleoclimatic setting of the Chinle basin was characterized by strong seasonality of precipitation; that is, distinct wet and dry seasons (Dubiel and others, 1991). However, interpretations of the paleoclimatic setting based solely on the Chinle flora have been somewhat varied, ranging from humid (Ash, 1972c; Ash and Creber, 1992) to arid (Daugherty, 1941; Gottesfeld, 1972). Although Dubiel and others (1991) attributed the discrepancy between their interpretation of the paleoclimate as seasonally wet and dry, and the interpretations of Ash (1972c) and Ash and Creber (1992) of a perennially wet paleoclimate to a preservational bias in the fossil flora, no detailed explanation of this bias was provided. However, Dubiel and others (1991), Ash (1972c) and Ash and Creber (1992) all concluded that changes in the vertical sequence of sedimentary facies and biofacies in the Chinle reflected an overall drying of the climate over the time of deposition.
The deposits of the Chinle Formation are fully continental. The lower part (Shinarump, Temple Mountain, Monitor Butte, Moss Back and Petrified Forest Members) is dominated by fluvial channel, overbank floodplain, paludal, and lacustrine deposits, whereas the upper part (Owl Rock, Rock Point and Church Rock Members) is characterized by fluvial, lacustrine, playa, and eolian sand sheet deposits (Dubiel, 1987, 1989a, 1994)(Figure 2). The delineation of uranium ore bodies in the Shinarump Member (Witkind, 1956) and stratigraphic studies of the relationships between the lower members of the Chinle (Stewart and others, 1972; Blakey and Gubitosa, 1984; Dubiel, 1989a, 1994) has shown that these units infill a large paleovalley system cut into the underlying Lower Triassic Moenkopi Formation before deposition of the Chinle. Smaller-scale paleovalleys, cut and filled during deposition of the lower part of the Chinle, also have been identified (Kraus and Middleton, 1987; Zuber, 1990). Detailed descriptions of plant-bearing facies and their depositional environments are provided in the description of the plant taphofacies below.

**Plant-bearing units**

Plant fossils in the Chinle Formation are preserved in fluvial channel, overbank, paleosol, and lacustrine delta deposits. As noted by Ash (1989a), abundant fossil plants are found mostly the lower part of the Chinle, including the Shinarump, Temple Mountain, Monitor Butte, Moss Back, and Petrified Forest Members. The few, rare plant fossils that have been found and described from the upper members have all been recovered from eroded talus blocks (Ash, 1982a, 1987a). Therefore, the following descriptions concentrate mostly on the lower, more fossiliferous part of the Chinle,
although reference is made to the depositional environments of the upper Chinle in the localities where plant fossils have been found. The localities where the plant assemblages in this study were described are shown on Figure 1, and their relative stratigraphic positions in the Chinle are noted on Figure 2.

The plant assemblages in the Chinle described below were delineated based on the depositional environment or subenvironment of the plant-bearing units (PBU's; herein defined as depositional units containing plant fossils). The description of these PBU's includes sedimentologic data including the: 1) lithology; 2) lateral extent; 3) thickness; 4) form; 5) continuity; and 6) order and arrangement of plant parts, and taphonomic data including the: 1) number of identifiable parts; 2) spatial density of plant parts; 3) size of remains; 4) predominance of organs; 5) preservational mode; 6) damage; 7) allochthony; and 8) diversity in the assemblages preserved in them. The use of these particular taphonomic parameters is based on the basic biostratinomic criteria used in evaluating plant fossil assemblages elucidated by Krasilov (1975) and those used in comparative taphonomic analysis of terrestrial vertebrate assemblages by Behrensmeyer (1991). The methodology for this analysis was as follows: 1) identification of well-exposed plant-bearing facies amenable to detailed study; 2) detailed sedimentological facies analysis of plant-bearing units; 3) identification and quantitative census of plant megafossils; and 4) assessment of relevant taphonomic characters of the assemblages.
Low-sinuosity channel PBU's

The fossil plants in low-sinuosity channel PBU's include some of the most famous fossils in the Chinle Formation, and are some of the most celebrated fossil plants in the world—the permineralized logs of Petrified Forest National Park (although some logs at Petrified Forest are preserved in the crevasse splay taphofacies, see below). These PBU's occur in conglomeratic sandstones (Shinarump and Petrified Forest Members (Figure 2) in Petrified Forest National Park, northeastern Arizona and southeastern Utah (Figure 1). The low-sinuosity channel deposits that contain these PBU's consist of light gray to light yellow, medium- to coarse-grained conglomeratic sandstone (Figure 3a). These sandstones occur as discrete, multi-story sand bodies, 10's of meters thick, confined within channel belts (Sonsela/Rainbow channel complex in the Petrified Forest Member) 10's of kilometers wide (Deacon, 1990), or paleovalleys (Shinarump Member) 100's of meters to several kilometers wide (Witkind, 1956; Stewart and others, 1972; Blakey and Gubitosa, 1984). The sediments are quartzose but contain locally abundant extrabasinal (chert and volcanic rock) and intrabasinal (mudstone and carbonate nodule) clasts and mudstone, siltstone and tuffaceous lenses. Internal stratification is characterized by large- to medium-scale trough cross bedding, medium- to small-scale planar cross bedding, horizontal bedding, and scour and fill. Down-paleocurrent stepping of bounding surfaces between cross bed sets indicates that downstream accretion of bedforms (mid-channel and lateral bars) was the dominant depositional process.

The only identifiable plant fossils found within the actively-filled low-sinuosity channel deposits (as differentiated from abandoned channels
Figure 3. Low-sinuosity channel PBU outcrops. A, channel-margin outcrop of Sonsela sandstone in Petrified Forest National Park; cliff face is about 8 m high. B, mid-channel outcrop of Sonsela sandstone at Petrified Forest National Park, note single *Araucarioxylon* log buried by trough cross-bedded conglomeratic sandstone.
discussed below) are permineralized tree trunks, identified by Knowlton (1889) as *Araucarioxylon arizonicum*. Although the assemblages of these trunks are well-known, their distribution is patchy. Within most outcrops of the low-sinuosity channel deposits in the Chinle, some permineralized wood can be found, usually as scattered logs (<1 log/100m² of aerial extent of a PBU) (Figure 3b). However, higher-density assemblages (up to 15 logs/100m² of aerial extent of a PBU) (Figure 4) do occur, especially in parts of the Sonsela/Rainbow sandstone in Petrified Forest National Park and near the base of paleovalleys filled by the Shinarump Member.

The order and arrangement (orientations) of the logs within the low- and high-density assemblages are different. The logs in the low-density assemblages, which are preserved within the main channel portions of the low-sinuosity channel deposits, are less ordered as a group (random), but tend individually to be oriented between oblique and perpendicular to paleocurrent directions as measured from cross beds in the PBU in which they are preserved (Table 1). The logs in the high-density assemblages, which tend to occur near the margins of the sand bodies or in confined paleovalleys, are more ordered and tend to be oriented sub-parallel to paleocurrent directions (Figure 5a) and channel trends (Figure 4).

Trunks preserved in low-sinuosity channel PBU's can be up to 1.5 m in diameter and 60 m long, but average about 1 m in diameter and 25 m long (Daugherty, 1941; Ash and Creber, 1992). Most trunks are slightly flattened subparallel to bedding, indicating that permineralization occurred sometime after burial, but before complete degradation. The trunks are permineralized with silica, preserving, to varying degrees, the cellular
Figure 4. Map of permineralized log in low-sinuosity channel deposits (Shinarump Member) near Monument Valley, AZ showing log orientations and their relationship to channel trend (after Witkind, 1956).
Table 1. Log orientations and paleocurrent measurements from the Sonselal/Rainbow sandstone at Rainbow Forest area, Petrified Forest National Park

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Average difference = 79°
Figure 5. Rose diagrams of log orientations and paleocurrent measurements. A, high-density assemblage from Sonsela/Rainbow sandstone at Long Logs area, Petrified Forest National Park; B, channel-lag assemblage from Newspaper Rock sandstone, Petrified Forest National Park; C, high-density assemblage from Black Forest bed, Petrified Forest National Park.
structure of the wood (Daugherty, 1941; Sigleo, 1979; Ash and Creber, 1992). Most of the silicified trunks were recrystallized during diagenesis, completely obliterating any preserved cellular structure (Ash and Creber, 1992). Trunks preserved in the Shinarump Member commonly have some original organic material preserved as a coaly rind around the silicified internal trunk cylinder (Witkind, 1956). Most of the logs are preserved as barkless, branchless cylinders from the root flare up, although some do have short portions of roots and branches attached (Daugherty, 1941; Ash and Creber, 1992). Evidence of damage preserved in and on the trunks includes fungal decay (Daugherty, 1941; Creber and Ash, 1990) and insect borings (Walker, 1938; S. Hasiotis, personal communication).

The distributions, orientations, and encasing sedimentary facies of the high- and low-density log assemblages in low-sinuosity channel PBU's indicate different modes and magnitudes of transport of the two types. The low-density assemblages, preserved in the middle of channels, are allochthonous. As with most trunks preserved in fluvial channels, these were introduced into the channels some distance upstream from the final burial site, most likely through overbank flooding and/or channel bank erosion through their growth sites (Spicer, 1991). After some indeterminate distance of transport, the logs were stranded on large barforms in the channel with their long axes oriented subparallel to the strike of the lee faces. Continued bedform migration buried the logs. The high-density assemblages, preserved along the margins of the channels, are parautochthonous; that is, they are preserved near their growth site, but because they are prone are not in situ. These logs were also introduced (toppled) into the channel by cut-bank
erosion; however, the trees were not transported by the stream, although some were rotated by the current, pivoting on the rootball, into a downstream-pointing direction. In the highest-density assemblages, interference between trunks (log jamming) hindered orientation. Subsequent bedform migration and channel aggradation buried the trees. The depositional setting of the low-sinuosity channel PBU's is shown schematically in Figure 6 along with a summary of sedimentologic and taphonomic characteristics.

*High-sinuosity channel PBU's*

High-sinuosity channel PBU's also contain woody material, although not in as spectacular a state as in the low-sinuosity PBU's. These PBU's are common, occurring in sandstones in the Petrified Forest Member (Figure 2) in Petrified Forest National Park (Figure 1) and Moss Back Member (Figure 2) in the White Canyon area of southeastern Utah (Figure 1). The high-sinuosity channel deposits that contain these PBU's consists of light brown to light gray, fine- to medium-grained sandstone with lenses and basal lags of mudchip and carbonate-nodule clasts (Figure 7). These deposits occur as discrete, single-storey sand bodies several meters thick and several kilometers wide (e.g., Newspaper Rock sandstone) and as multi-storey sand bodies 10's of meters thick and 10's of kilometers wide (e.g., Moss Back Member) and commonly are the basal fill of incised paleovalleys (Blakey and Gubitosa, 1984). The internal stratification of these sand bodies is characterized by small- and large-scale trough and planar cross beds, ripple cross lamination, and large-scale lateral accretion surfaces. Conglomerates and large-scale trough cross bed sets in the basal portions of these units
Figure 6. Schematic depositional model of low-sinuosity channel PBU's and summaries of sedimentologic and taphonomic characteristics. ms, mudstone; silt, siltstone; ss, sandstone; congl, conglomerate; permin, permineralized; adpress, adpression; autoch, autochthonous; paraautoch, paraautochthonous; alloch, allochthonous.
Figure 7. Outcrops of high-sinuosity channel deposits; note lateral accretion beds. A, Temple Mountain Member, San Rafael Swell, UT (mine in center is ~2 m high); B, Newspaper Rock sandstone, Monitor Butte Member, Petrified Forest National Park (sandstone is 10 m thick in center of picture).
represent deposition by bedform migration and channel aggradation in the deeper portions of the channels, whereas small-scale trough and planar cross-beds and ripple cross lamination within lateral accretion sets record deposition by bedform migration during point bar migration.

The dominant plant fossils in the high-sinuosity channel PBU's are coalified, cast, and silicified trunks and stems. These xylic elements are present in the lowest parts of the units at the channel base, and on the upper parts of lateral accretion surfaces. The woody material in the basal assemblages is abundant, although patchy in distribution, reaching densities of 3-5 trunks/m² in log jams that cover 4-10 m² (Figure 8a). These small jams are present in scoured depressions at the base of the sand bodies. About half of these trunks are hollow and cast by sandstone. These trunks and stems range in size between 0.05-0.5 m in diameter and 0.5-2.0 m in length. The trunks have no lateral branches or roots preserved; however, some individual specimens with forked trunks are present. Hollow, cast trunks are circular to oval in cross section, whereas solid trunks are flattened. All of these fossils are degraded, abraded, and poorly preserved. They are not assignable to any known genus; however, the hollowed trunks broadly resemble those of Neocalamites, whereas the flattened trunks are probably those of gymnosperms. The trunks are oriented parallel to paleocurrents (Figure 5b). Assemblages preserved on the upper parts of lateral accretion surfaces are composed of branches, stems, and small trunks ranging in size between 0.05-0.2 m in diameter and 0.5-1.0 m in length. Their distribution is patchy, although most lateral accretion sets preserve at least some dispersed
Figure 8. Coalified and cast logs from high-sinuosity channel deposits. A, log jam at base of Newspaper Rock sandstone, Petrified Forest National Park (knife for scale); B, branches and stems on upper part of lateral accretion surfaces, Moss Back Member, White Canyon, UT (pencil for scale).
material. Density of plant parts within these assemblages is highly variable, from <1 to >100 stems/m² (Figure 8b).

The coalified and cast trunks, stems, and branches present in the high-sinuosity channel PBU's are allochthonous xylic elements that were buried after transport as bedload and suspended load. They were most likely part of the arborescent riparian streamside vegetation and were introduced into the channel environment by cut-bank erosion during channel migration and floodplain erosion during overbank flooding. The trunks were trapped in small log jams in deeper pools near the thalweg of the channel, oriented by the prevailing stream currents, and subsequently buried by large three-dimensional ripples that filled in the scours. The assemblages preserved on the upper parts of lateral accretion surfaces were carried as suspended load in the streams and were stranded on point bars during waning flow. Poor preservation of these assemblages resulted from degradation and abrasion in the channel environment prior to burial, and also from burial in relatively coarse sediment. Except for assemblages in the Shinarump Member, none of this material was silicified. The absence of abundant volcanic material in the surrounding sediments as a source of dissolved silica, as compared to the low-sinuosity channels previously discussed, precluded early silicification of the woody material. Material not cast by sediment was flattened after burial and the remaining organic material was coalified. The depositional setting of the high-sinuosity channel taphofacies is shown schematically in Figure 9.

Abandoned-channel PBU's

Abandoned-channel PBU's preserve fossil plants in dark gray to black, carbonaceous mudstone- and siltstone- and fine-grained sandstone-filled,
Figure 9. Schematic depositional model of high-sinuosity channel PBU's. Abbreviations as in Figure 6.
lens-shaped, linear bodies laterally adjacent to, and interfingering with, both high- and low-sinuosity channel deposits (Figure 10). This taphofacies is associated with fluvial sandstones in the Shinarump and Petrified Forest Members (Dubiel, 1994) and in the Monitor Butte Member in White Canyon, UT (Dubiel, 1994) and Fort Wingate, NM (Ash, 1978a). These deposits are thin (<2 m) and are not laterally extensive, usually covering <1 km² in areal extent. Internal stratification is characterized by thin laminations (1-10 mm thick) and localized bioturbation. These deposits typically fine upward, and are rootworked at the top. Fossil conchostrachans and aquatic vertebrates are commonly found in these deposits.

The fossil plants preserved in the abandoned-channel PBU's include partial leaves and pinnules of cycadeiods (Zamites powelli and Nilssoniopteris sp.), shoots and needles of conifers (Pagiophyllum sp.) and the protognetalean? Dinophyton spinosus, and stems and rhizomes of horsetails (Neocalamites and Equisetites) and lycophytes (Isoetites). Although the foliar material is fragmentary (plant parts <10 cm in long dimensions), it is abundant (10-50 parts/m²) and well-preserved (coalified compressions with original cuticle). The rhizomes and some stems of horsetails are cast in situ, whereas lycophyte stems are preserved broken and prone as coalified compressions. All of the material is disordered and randomly oriented.

The abandoned-channel deposits that preserve these plants were formed by the infill of oxbow lakes and moribund channels. These channel segments were abandoned during migration and avulsion of the Chinle streams. After abandonment, the channels were filled by fine-grained
Figure 10. Outcrop of abandoned-channel deposits associated with the Sonsela/Rainbow sandstone, Petrified Forest Member, Petrified Forest National Park. Dark layers are bedded cuticular material. Pen for scale.
sediment deposited by suspended load fall-out during overbank flooding. The abandoned-channel PBU's preserve both allochthonous and autochthonous material. The fragmentary foliar material was transported into the channels with flood waters and fine-grained sediment and, possibly, by wind. Between flood events, semi-aquatic and wetland plants (horsetails and lycophytes) grew in and along the edges of the channels. These plants, and the litter they produced, were buried in place. After complete infill of the old channels, the sediment surface was colonized by mesic plants and pedogenically modified. The depositional setting of the abandoned channel fill PBU's is shown schematically in Figure 11.

*Crevasse-splay PBU's*

Fossil plants in crevasse-splay PBU's are preserved in thin (>2 m) lobe-shaped sheets of light brown and greenish gray to olive gray mudstone, silty mudstone, siltstone, and very-fine grained sandstone laterally adjacent to and interfingering with levee and channel deposits. These PBU's occur in overbank deposits laterally equivalent to fluvial sandstones in the Monitor Butte Member (Figure 2) in Petrified Forest National Park and near Fort Wingate, NM (Figure 1). These sheet-like deposits occur as single units in otherwise finer-grained floodplain mudstone intervals or as stacked, multiple fining-upward sequences (Figure 12). The splay units are thickest near channels and pinch out into floodplain mudstones away from the channels; the splays cover areas 1-10 km$^2$. Internal stratification is characterized by climbing-ripple cross lamination, small-scale trough cross beds, and upper-stage plane beds. The tops of splay
**Figure 11.** Schematic depositional model of abandoned-channel PBU's. Arrows show routes of allochthonous material. Abbreviations same as in Figure 6.

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Figure 12. Outcrop of crevasse-splay deposits, Monitor Butte Member, Tepees area, Petrified Forest National Park. Note stacked, fining-upward units. Person for scale.
units are commonly bioturbated and exhibit weak to moderate pedogenic modification (rootworking, carbonate and iron nodules, color mottling).

The Black Forest bed, which is in the Petrified Forest Member (Figure 2) where it crops out in the Painted Desert area of Petrified Forest National Park (Figure 1), appears to be a different type of large crevasse-splay deposit. It covers ~80 km² and is up to 14 m thick and is composed of a basal carbonate-nodule conglomerate up to 6 m thick and light gray, fine- to medium-grained tuffaceous sandstone up to 8 m thick. Internal stratification consists of large- and small-scale trough cross beds, scour-and-fill, and upper-stage plane beds. The upper meter is pedogenically modified. The Black Forest bed has been interpreted to have been deposited by an avulsion event associated with a contemporaneous volcanic ash fall (Riggs and others, 1994), and the taphonomy of the fossil plants preserved in it are discussed separately below.

Plants preserved in crevasse-splay PBU's include horsetail (Neocalamites) stems, leaves, and rhizomes (Daugherty, 1941; Holt, 1947) (Figure 13). Specimens of stems and attached strap-like conifer leaves (Pelourdea poleonensis) found in Big Indian Valley, UT (Figure 1)(Ash, 1987a) and palm-like leaves of the proto-angiosperm? Sanmiguelia lewisii found in Capitol Reef National Park (Figure 1)(Ash, 1982a), although described from talus blocks, appear to have come from crevasse splay deposits associated with channels in the upper part of the Chinle (Owl Rock and Church Rock Members; Figure 2). One taphonomic feature common in crevasse splay assemblages is the preservation of at least some plants in situ. The stems and trunks of horsetails in the crevasse-splay taphofacies are commonly
Figure 13. *Neocalamites* leaf litter on a bedding surface in crevasse-splay deposits, Monitor Butte Member, Petrified Forest National Park. Samples are part and counterpart.
preserved erect with hollow internal cavities filled by sediment (Daugherty, 1941; Holt, 1947; Ash, 1972c). Ash (1987a) also described specimens of *Pelourdea poleonsis* as having been preserved erect and *in situ*. Abscised foliar elements in the crevasse-splay PBU's are preserved as compressions on bedding planes, usually near the base of the splay unit. Spatial density of plant parts ranges from 1-2 parts/m² in erect stem/trunk assemblages, to 5-10 parts/m² in bedding plane litter assemblages. Orientation of plant parts is random, although Ash (1987a) attributed a slight bending of erect stems of *Pelourdea poleonsis* to action by currents during burial.

The fossil plants in the crevasse-splay PBU's were preserved by crevasse-splay events. The plants grew in overbank areas proximal to fluvial channels and were subject to catastrophic burial during levee-breaching flood events. Erect stems and parautochthonous surface litter were buried *in situ*. As pointed out by Demko and Gastaldo (1992) and Gastaldo (1992), horsetails are able to withstand burial of their stems and continue growth, and such was probably the case with *Neocalamites* in the crevasse-splay taphofacies; other plants were likely killed. The new sediment surface was then colonized by pioneering plants. In the case of stacked splay sequences, repeated crevasse events buried a series of land surfaces. The depositional setting of crevasse-splay PBU's is shown schematically in Figure 14.

The Black Forest bed in Petrified Forest National Park is named for the dark-colored, permineralized gymnosperm trunks it preserves. Prone trunks and *in situ* stumps of *Araucarioxyylon arizonicum* are the dominant plant fossils, with smaller quantities of prone *Woodworthia arizonica* and *Schilderia adamanica* logs also present (Daugherty, 1941; Ash, 1992). The
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Figure 14. Schematic depositional model of crevasse-splay PBU's and summary of sedimentologic and taphonomic characteristics. Abbreviations same as in Figure 6.
gymnosperm trunks and stumps in the Black Forest bed are silicified with the cellular structure of the wood well preserved. The logs are up 54 m in length and 1.75 m in diameter, although they average 12 m in preserved length and 0.9 m in diameter. Most are preserved slightly flattened. They are concentrated in the lower 2 m of the tuffaceous sandstone bed and reach densities of up to 12 logs/100m². Erect, in situ stumps, 1-1.5 m in diameter with preserved trunk sections up to 3 m in height, are common (Figure 15). These stumps are rooted in an underlying purple mudstone paleosol and buried by the Black Forest bed (see paleosol PBU section below). Some logs show damage, including insect borings and channels (Walker, 1938) and fire scars (J.T. Parrish and K.M. Gregory, personal communication). Ash (1992) reported that a random sample of 110 Black Forest logs to have widely dispersed orientations, with a preferred direction to the north (bases pointing south). However, a sample of 37 logs from a dense accumulation in a 2 km² region in the central portion of the Black Forest bed exposure area shows a strong preferred orientation to the west-northwest (Figure 5c).

The Black Forest bed is an avulsion-related splay deposit that preserves both autochthonous and parautochthonous logs. The logs and stumps were buried by catastrophic avulsion of a stream system into an overbank forest, probably caused by rapid channel aggradation due to overloading by volcanic ash (Riggs and others, 1994). The currents were strong enough to erode deeply into the floodplain in some areas, at least down to soil horizons with pedogenic carbonate nodules. Trees in these areas were undercut, toppled and probably transported short distances and oriented by currents. These trunks formed the prone assemblages. In other areas, the
Figure 15. Erect, in-place *Araucarioxylon arizonicum* stump, Black Forest bed, Petrified Forest Member, Petrified Forest National Park.
bases of trees were buried by up to 10 m of tuffaceous sand and transported carbonate nodules. The lower parts of the stumps of these trees and the buried prone logs were permineralized by abundant dissolved silica from the volcanic ash.

Lacustrine-delta PBU's

Fossil plants in lacustrine-delta PBU's are preserved within stacked, coarsening-upward, mudstone, siltstone, and fine-grained sandstone units (Figure 16). In the study area, these deposits only occur in the Monitor Butte Member (Figure 2) in southeastern Utah (Figure 1). These units are 1-2 m thick and are characterized by climbing-ripple cross lamination, horizontal lamination, and soft-sediment deformation structures (slumps). The tops of some units are rootworked. The lacustrine-delta deposits are laterally adjacent to, and interfingers with, paludal and fluvial channel/levee deposits.

The fossil plant assemblages preserved in lacustrine-delta PBU's are dominated by cycadeoids (Zamites powelli) and horsetails (Neocalamites), but also include ferns (Phlebopteris smithii) and the protognetalean? Dinophyton spinosus. Fragmented and whole pinnate leaves of cycadeoids, horsetails and ferns, along with abscised shoots and samaras of Dinophyton spinosus are preserved as coalified compressions in the lower parts of the coarsening-upward units. Horsetail stems are preserved upright and in situ and also as prostrate casts. Although dispersed organic material (phytoclasts) is abundant in lacustrine-delta deposits in the Chinle (Dubiel, 1989a), assemblages of plant megafossils are patchy, occurring only near the upper parts of delta foresets. The size of remains (2-10 cm long axis) and
Figure 16. Lacustrine delta deposits, Monitor Butte Member, White Canyon, UT.
densities of plant parts in these assemblages are variable (1-8 parts/m²) and all are disordered and randomly oriented.

The taphonomy of the fossil plants in lacustrine delta PBU's is similar to both crevasse-splay PBU's previously discussed and paludal-overbank PBU's discussed below. This is because lacustrine deltas in the Chinle were simply splay deposits that were deposited into standing water (floodplain lakes) (Pierson, 1984; Dubiel, 1989a) rather than onto subaerially exposed floodplains. The fragmentary plant fossils preserved are allochthonous, transported as suspended load during active sedimentation on the deltas. Whole leaves are parautochthonous, probably transported short distances from growth sites on the subaerial portions of the deltas, and erect horsetail stems were buried in place in their growth sites at the margins of the deltas. The depositional setting of the lacustrine-delta PBU's is shown schematically in Figure 17.

**Paludal-overbank PBU's**

Paludal-overbank PBU's preserve most of the foliar elements found in the Chinle Formation. In fact, most of these fossil plants have been described from one single locality in this type of PBU. Paludal-overbank deposits in the Chinle are composed of light gray, olive gray, and greenish gray mudstone and silty mudstone (Figure 18) and coal (Figure 19). Characteristic sedimentary structures in the mudstone facies include parallel lamination, micro-scale cross lamination, and rootworking. These mudstone facies often are characterized by barely discernible bedding in which individual beds, 0.5-1 m thick, consist of fining-upward sequences from mudstone or silty
Figure 17. Schematic depositional model of lacustrine-delta PBU's and summary of sedimentologic and taphonomic characteristics. Abbreviations same as in Figure 6.
Figure 18. Paludal-overbank deposits (light gray units below striped unit) Monitor Butte Member, Petrified Forest National Park. Site of Daugherty's (1941) "leaf shale" unit, and locality from which a majority of the fossil plants from the Chinle Formation have been described. Note that unit is the basal unit in a paleovalley infill sequence.
Figure 19. Coal seam, Monitor Butte Member, White Canyon, UT.
mudstone to siltstone. The tops of these beds are completely rootworked and bioturbated. Coal beds, 0.2-1.0 m thick, consist of banded bright and dull laminations and layers with abundant carbonaceous mudstone laminations and partings.

Compressions of pinnate leaves from the cycadeoid *Zamites powelli* (Figure 20) are the dominant plant fossil preserved in the mudstone-dominated paludal-overbank PBU's. Compressions of pinnate leaves and individual pinnae from the cycad *Aricycas paulae*, attached pinnate leaves and rachi of the fern *Phlebopteris smithii*, leafy shoots and samaras from the protognetalean? *Dinophyton spinosus*, and pinnules of the cycadeoid *Nilssoniopteris* sp. are also locally abundant. These foliar elements are coalified and the original cuticle is often preserved. Other plant fossils preserved in these PBU's include coalified and partially pyritized stumps and prostrate logs (unassignable, but probably conifers). The size of preserved plant parts ranges from 2 cm (pinnules and samaras) to >20 cm (rachi and logs). Fossil plants are concentrated along the bases of beds and reach densities as high as 80 parts/m². Identifiable plant fossils are not present in the coal beds; however, poorly preserved fossils within mudstone partings suggest that the original peat was composed of cycadeoid and fern material.

The fossil plants preserved in the paludal-overbank PBU's represent autochthonous and paraautochthonous elements of herbaceous and arborescent wetland vegetation. Abundant cycadeoids and ferns and subdominant cycads, protognetaleans?, conifers, and other plants formed the standing vegetation and surface litter in overbank wetland areas in proximal floodplain
Figure 20. Plant fossils from the paludal-overbank deposits, Monitor Butte Member, Petrified Forest National Park. A, *Zamites powelli* frond; B, *Aricycas paulae* frond; C, *Phlebopteris smithii* rachi attached to petiole.
environments (clastic swamps). These plants and the surface litter layer they generated were repeatedly buried by sedimentation during overbank flood events. The surface litter layer, consisting mostly of abscised cycadeoid leaves, was preserved by initial suspension load fall-out and was not transported. Coal seams in the Chinle were deposited as autochthonous and parautochthonous litter in peat-accumulating swamps in overbank wetland areas. The peat in these wetlands was buried by sedimentation during overbank flooding. The depositional setting of paludal-overbank PBU's is shown schematically with a summary of the sedimentologic and taphonomic characteristics of the paludal-overbank taphofacies in Figure 21.

**Paleosol PBU's**

Fossil plants in paleosol PBU's are preserved in and on reddish brown and reddish purple massive mudstones. These mudstones are smectitic and have features indicative of pedogenesis including color mottling, carbonate and iron nodules, large curving slickenside surfaces, and back-filled, meniscate burrows (*Scoyenia* sp.). These units are 1-5 m thick and are often in stacked sequences. Paleosol PBU's occur in the Petrified Forest Member in Petrified Forest National Park.

Fossil plants preserved in the paleosol PBU's include permineralized (silicified) stumps, prone logs, and roots (Figure 22). This xylic material is typically poorly preserved; some stumps and some logs have been assigned to *Araucarioxylon* sp. (Ash and Creber, 1992). Stumps are preserved to heights of only 0.5 m or less, although a few taller ones are preserved (including those in the Black Forest bed, see discussion of crevasse-splay taphofacies above), some as high as 6 m above the root flare (Ash and Creber, 1992). An
Figure 21. Schematic depositional model of paludal-overbank PBU’s and summary of sedimentologic and taphonomic characteristics. Abbreviations same as Figure 6.
Figure 22. Permineralized woody material from paleosol taphofacies, Petrified Forest National Park. A, poorly preserved roots, Petrified Forest Member, pen for scale. B, *in situ* stump with roots preserved, Black Forest bed.
assemblage of 40 stumps in the Petrified Forest Member in Petrified Forest National Park has densities of 1-5 stumps/100 m$^2$ (Gottesfeld, 1972; Ash and Creber, 1992). Prostrate logs (0.2-0.5 m diameter, > 10 m long) are flattened, and reach densities of 3-4 logs/100 m$^2$. Roots are preserved as silicified, flattened, tapering bodies 0.2-0.3 m in diameter within the top 1.0-1.5 m of the paleosols. Creber and Ash (1990) attributed the poor preservation of a stump and prone log assemblage in one such paleosol taphofacies to fungal decay. The fossil plants in paleosol PBU's are disordered and show no preferred orientation.

The trunks, logs, and roots in paleosol PBU’s are autochthonous xylic elements buried in situ in and on the soils on which they grew. Pedogenic features in these soils suggest that they were well-drained. Burial of the bases of trees and prostrate trunks by catastrophic flooding (probably avulsions), or possibly airborne volcanic ash, preserved them in or close to their original growth sites. The overall poor preservation of this material, however, indicates that it must have been decaying at or near the surface for sometime before silicification. The depositional setting of paleosol PBU’s is shown schematically with a summary of the sedimentologic and taphonomic characteristics in Figure 23.

**Summary and Discussion**

Fossil plant assemblages in the Chinle Formation are preserved in seven types of plant-bearing units (PBU’s) deposited in different depositional environments. (1) Low-sinuousity channel PBU’s, present in the Shinarump Member and Sonsela sandstone of the Petrified Forest Member,
Figure 23. Schematic depositional model of paleosol PBU's and summary of sedimentologic and taphonomic characteristics. Abbreviations same as Figure 6.
contain silicified gymnosperm trunks preserved in dispersed assemblages in mid-channel facies, and concentrated assemblages in channel-margin facies. The logs in mid-channel assemblages are autochthonous and are oriented oblique to paleocurrents, and those in channel-margin assemblages are paraautochthonous and are oriented sub-parallel to paleocurrents. (2) High-sinuosity channel PBU's, present in the Shinarump, and Moss Back Members, and the Newspaper Rock sandstone of the Petrified Forest Member, contain silicified, coalified, and cast gymnosperm trunks, branches and stems, preserved in concentrated assemblages in basal channel lags and on the upper parts of point bars. These assemblages tend to be current oriented. (3) Abandoned channel PBU's, present in the Petrified Forest Member, contain allochthonous coalified impressions of cycadeoid leaves and conifer shoots and autochthonous stems and rhizomes of horsetails and lycophytes. These assemblages are disordered and randomly oriented. (4) Crevasse-splay PBU's, present in the Monitor Butte Member, contain in-place cast stems of horsetails and associated litter layers. Crevasse-splay PBU's in the Owl Rock and Church Rock Members contain compressions of in-place conifer stems and leaves and the compression leaves of a proto-angiosperm (Sanmiquelia). The Black Forest bed, an avulsion-related splay deposit in the Petrified Forest Member in Petrified Forest National Park, preserves autochthonous silicified gymnosperm stumps and oriented paraautochthonous silicified gymnosperm logs. (5) Lacustrine delta PBU's, present in the Monitor Butte Member, contain autochthonous casted horsetail stems, and allochthonous and paraautochthonous coalified impressions of cycadeoid and fern leaves, and protognetalean? shoots and samaras. (6) Paludal overbank
PBU's, present in the Shinarump and Monitor Butte Members, contain autochthonous and paraautochthonous coalified compressions of cycadeoid, cycad and fern leaves, protognetalean? shoots and samaras, and prostrate and erect gymnosperm trunks and logs. Thin coal seams, deposited in peat-accumulating overbank swamps, are included in these PBU’s. These assemblages are concentrated, disordered and unoriented. (7) Paleosol PBU's, present in the Petrified Forest Member, contain autochthonous and paraautochthonous, silicified gymnosperm trunks, stumps, and roots. These assemblages are locally concentrated, disordered, and randomly oriented. The summaries of the sedimentologic and taphonomic characteristics of these PBU's are displayed together in Figure 24.

With the exception of paleosol PBU's, the Chinle plant PBU's are characterized by wet environments of deposition (fluvial channels, overbank floodplains, deltas, and wetlands). The units that bury the paleosol PBU's, however, also are characterized by wet environments of deposition.

Depositional settings of PBU's in the Chinle would have been characterized by flowing or standing water of some depth and/or high water tables (at or very near the surface). Burial under these types of conditions is conducive to preservation of plant tissues (Spicer, 1991) and, in the case of xylic material buried in tuffaceous sediments, conducive to early silicification (Sigleo, 1979). However, allochthonous and paraautochthonous material in the Chinle taphofacies did not necessarily come from plants that grew in these
Figure 24. Comparative taphonomy of plant-bearing units in the Chinle Formation. Abbreviations same as Figure 6.
types of hydric edaphic conditions (e.g., prostrate gymnosperm trunks in the channel taphofacies). These elements were transported, at least some distance, from their growth sites. Bank erosion due to channel migration and floodplain scouring during overbank flooding introduced plant material from more mesic growth sites into fluvial environments both as bedload and suspended load. This material was incorporated into the channel (basal lags, mid-channel and lateral bars) or overbank deposits (splays, deltas, and abandoned channels). However, the taphonomic characteristics of these elements (concentration, arrangement, orientation, damage, etc.) and the autochthonous elements in these and other PBU's make discrimination possible.

Since the relative allochthony of the elements in the Chinle taphofacies is discernable, something can be said about the composition of vegetational communities from which they were derived based on the relative abundance of autochthonous and paraautochthonous taxa. Clastic swamps (paludal areas characterized by hydric mineral soils) and peat swamps (paludal areas characterized by histosols), present in proximal floodplain areas and along the margins of overbank lakes, were dominated by herbaceous cycadeoids and ferns, with subdominant small-statured conifers. Fringing semi-aquatic areas, present along the margins of overbank lakes and abandoned channels, were dominated by arborescent and herbaceous horsetails, with subdominant herbaceous lycophytes and cycadeoids. Well-drained areas of the alluvial valleys on the Chinle landscape, present in distal floodplain areas, interfluves, and on alluvial ridges (levees), were populated by arborescent gymnosperms. In the upper members of the Chinle, the few fossil plant
assemblages that have been found suggest that some well-drained floodplain areas were populated by herbaceous to semi-arborescent gymnosperms and proto-angiosperms. It must be remembered that these interpretations are based on the relative abundances of preserved fossils in the assemblages, which, in some cases, actually reflect the surface litter rather than standing biomass or relative abundances of individual plants. This caveat is especially important in light of Ash's (1975, 1991) interpretations of the cycadeoid *Zamites powelli* (the most abundant plant fossil in the Chinle) and the cycad *Aricycas paulae* as having been deciduous. If these plants were deciduous, preserved litter layers may be biased compositionally towards them, because they may be responsible for several crops of material in the surface litter layer. However, most litters in the Chinle consist of a single layer of leaves, and most individual plant parts in a particular litter are in the same state of preservation, suggesting that they are from the same seasonal crop.

In conclusion, the fossil plant assemblages in the Chinle Formation were preserved in a mosaic of terrestrial depositional settings on the Late Triassic landscape of western North America. Most plant-bearing units are located in the lower members (Temple Mountain, Shinarump, Monitor Butte, and Petrified Forest Members), which infill a large paleovalley system cut into the underlying Moenkopi before Chinle deposition and smaller paleovalleys cut into the Chinle itself during deposition (Blakey and Gubitosa, 1984; Kraus, 1987; Dubiel, 1994). These plant assemblages were derived from riparian and wetland vegetational communities extant in the fluvial and lacustrine systems confined in these paleovalleys. For this reason, the Chinle flora is taphonomically biased towards environments
characterized by wet edaphic conditions in these paleovalleys, and probably does not reflect conditions in drier upland areas within and around the depositional basin.
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Ash, S.R. and Creber, G.T., 1992, Palaeoclimatic interpretation of the wood structures of the trees in the Chinle Formation (Upper Triassic),


Zuber, D.J., 1990, Geochemistry and sedimentology of paleosols in the Upper Petrified Forest Member, Chinle Formation, Petrified Forest National Park, Arizona: M.S. Thesis, Northern Arizona University, 158 p.
Appendix C: Incised-valley fills and the taphonomy of fossil plants: An example from the Upper Triassic Chinle Formation, Colorado Plateau, USA

Abstract

The fossil plant assemblages of the Upper Triassic Chinle Formation are concentrated in the lower members (Shinarump, Temple Mountain, Monitor Butte, and lower part of the Petrified Forest Members) of the formation. The upper part of the formation (upper Petrified Forest, Owl Rock, and Church Rock/Rock Point Members) have comparatively few preserved fossil plants. The lower part of the Chinle Formation was deposited in an incised valley system cut into underlying Lower-Middle Triassic and older rocks. Depositional, hydrological, and near-surface geochemical conditions in the incised valley system were conducive to preservation of terrestrial organic material, even though regional conditions were characterized by seasonal precipitation and groundwater conditions. Fossil plant assemblages in fully terrestrial incised valley-fills, like the lower part of the Chinle Formation, should be taphonomically biased towards riparian wetland environments. This should be taken into account when using these types of plant assemblages in paleoclimatic interpretations.

Introduction

The lower part of the Upper Triassic Chinle Formation in the Colorado Plateau region was deposited in an incised-valley system (Stewart and others, 1972; Blakey and Gubitoso, 1983, 1984). Abundant plants (Ash, 1972, 1989a), vertebrates (Long, 1986; Parrish, 1989), and trace fossils
(Hasiotis, 1994) are found in these units. The fossil plant assemblages, which include cycadeoids, cycads, ferns, conifers, horsetails, and other plants, are preserved in fluvial channels and overbank areas, lacustrine deltas, and in paleosols. The upper part of the Chinle Formation, which was deposited in fluvial, lacustrine, and eolian environments, is characterized by a paucity of plant fossils as compared to the lower part of the formation. Only a few plant fossil assemblages, which contain conifers, horsetails, and a supposed proto-angiosperm, have been reported (Ash, 1987) in the upper members.

The concentration of plant fossil assemblages in the lower part of the Chinle Formation, and their taphonomic characteristics, was controlled by sedimentological and hydrological factors related to infill of the incised paleovalley system. Base-level fluctuations, both climatically and tectonically controlled, before and during infill of the paleovalley were important in generating local accommodation space for preservation of plant-bearing facies, whereas perennially high water tables within the valley-fill sediments provided favorable near-surface geochemical conditions conducive to preservation of organic material.

**Geologic setting**

The Chinle Formation was deposited in a broad, fully terrestrial, cratonic basin on the western margin of Pangea, interpreted by (Lawton, 1994) as a back-bulge basin created by subsidence due to viscous flow in the mantle associated with the subduction of the Farallon plate and flexure due to supracrustal loading by the associated volcanic arc (Figure 1). During the Late Triassic, sediments were deposited extensively over western North America (Dubiel, 1994) and the Colorado Plateau/Four Corners region was a
Figure 1. Paleogeographic map of the Chinle depositional basin showing position of magmatic arc, forebulge, Ancestral Rockies (from Lawton, 1994), and paleovalley systems filled by the lower part of the Chinle Formation (from Stewart and others, 1972; Blakey, 1989; and Dubiel, 1994). Lines of section A-A' and B-B' for Figure 2. PD-Painted Desert paleovalley, VC-Vermillion Cliffs paleovalley, E-Paint Desert paleovalley. Measured section localities: PA-Paria, R-Rincon, MB-Monitor Butte, CR-Comb Ridge, PF-Petrified Forest, L-Lupton, FW-Fort Wingate, P-Prewitt.
regional depocenter (Blakey, 1989). In the Four Corners area the Chinle is more than 500 m thick (Dubiel, 1989b). Sediments deposited in the Chinle basin came from source areas in the remnants of the ancestral Rocky Mountains to the east of the basin (Blakey and Gubitosa, 1983; Dubiel, 1994), uplifted Paleozoic rocks and possible arc-related volcanic rocks to the south (Stewart and others, 1972, 1986), and as wind-transported volcanic ash from contemporaneous arc-related eruptions to the southwest and west of the basin (Stewart and others, 1986; Riggs and others, 1994).

Paleogeographic reconstructions of Pangaea, based on paleomagnetic data, place the Chinle basin in the tropical belt 5°-10° north of the Late Triassic equator (Witte and Kent, 1989; Bazard and Butler, 1991). Sedimentological evidence, including vertic paleosols and cyclic lacustrine deposits suggest that the paleoclimatic setting of the Chinle basin was characterized by strong seasonality of precipitation, that is, distinct wet and dry seasons (Dubiel and others, 1991). Paleontological evidence, including crayfish and lungfish ichnofossils, growth bands in unionid bivalves, and taphonomic characteristics of some vertebrate assemblages indicating desiccation and trampling prior to burial supports this interpretation (Dubiel and others, 1991).

Incised-valley fills in the Chinle Formation

Three major paleovalley systems at the base of the Chinle Formation are recognized in the Colorado Plateau region: 1) the Painted Desert paleovalley (discussed in detail this paper); 2) the Vermillion Cliffs paleovalley; and 3) the Eagle paleovalley (Blakey and Gubitosa, 1983; Dubiel, 1994) (Figure 1). In addition several major tributaries to these systems have
also been identified and named including the White Canyon, Cottonwood (Blakey and Gubitosa, 1983), Moab, and Temple Mountain paleovalleys (Dubiel, 1994). The major incised valleys were cut into the underlying Moenkopi Formation over most of the Colorado Plateau, and into the Permian and older rocks near the eastern margin of the Chinle depositional area (Stewart and others, 1972). The paleovalley systems are up to 150 km wide and 120 m deep, and individual valleys in these systems are up to 90 m deep and 8 km wide (Blakey and Gubitosa, 1983, 1984). Lawton (1994) has suggested that this period of incision was initiated by uplift of a dynamic forebulge on the western edge of the North American craton and continued due to a downward base-level shift caused by overspill from the back-bulge basin into the back-arc basin. The youngest rocks below the unconformity at the base of the Chinle are Middle Triassic (Anisian) (Stewart and others, 1972) and the oldest rocks above the unconformity are Upper Triassic (Carnian) (Litwin and others, 1991), a lacuna of 25 million years.

The Shinarump, Temple Mountain, Monitor Butte, Moss Back, and part of the Petrified Forest Members of the Chinle Formation represent the paleovalley infill sequence of the Painted Desert paleovalley system (Blakey and Gubitosa, 1983, 1984; Blakey, 1989) (Figure 2). Although the Shinarump Member is most commonly the lowest stratigraphic unit in the infill sequence, an interval of pedogenically modified older rocks and basal Chinle, informally called the "mottled strata", is often present near the base of the formation (Stewart and others, 1972). The Temple Mountain Member, the basal member of the Chinle in the San Rafael Swell area, contains both sandstone channel deposits and color-mottled finer-grained rocks and is
Figure 2. Generalized cross sections of the lower part of the Chinle Formation across the Painted Desert paleovalley showing occurrences of fossil plant assemblages. Lines of section A-A' and B-B' on Figure 1.
equivalent to both the mottled strata and the Shinarump Member (Stewart and others, 1972; Dubiel, 1992). In the Painted Desert paleovalley, the mottled strata represent a period of non-deposition and/or sporadic and patchy deposition between the time of paleovalley incision and infill. Color mottling and the presence of crayfish burrows in this unit are evidence of fluctuating water tables and gleying during pedogenesis (Dubiel and others, 1991). The Shinarump Member is typically composed of two distinct units of quartzose sandstone: 1) a lower conglomeratic sandstone characterized by crude trough and tabular cross beds that infill the lowest channels of the paleovalleys, and 2) an overlying medium- to coarse-grained sheet sandstone characterized by tabular cross beds, that is more regionally extensive (Davidson, 1967; Blakey and Gubitosa, 1984; Haney, 1987). The Shinarump also contains variable amounts of interbedded siltstone and mudstone beds, in some instances making up 60% of the unit, but more typically <10% (Blakey and Gubitosa, 1984). The thickness of the Shinarump ranges from more than 90 m near the deepest parts of the paleovalleys to zero where it pinches out against the paleovalley walls (Stewart and others, 1972). The Shinarump sandstones have been interpreted to have been deposited in bed-load dominated low-sinuosity streams (Blakey and Gubitosa, 1983; 1984; Pierson, 1984; Dubiel, 1987; Haney, 1987), although some outcrops of conglomeratic sandstone in the lowest parts of paleovalleys do have evidence of significant deposition by lateral accretion (Blakey and Gubitosa, 1984).

The Monitor Butte Member overlies and interfingers with the Shinarump Member and is predominantly composed of olive-gray to greenish gray smectitic mudstone and siltstone, but also contains fine-grained
tuffaceous sandstone, laminated carbonaceous mudstone and shale (Stewart and others, 1972). In the White Canyon area of southeastern Utah, the Monitor Butte also contains thin limestones and coal seams (Pierson, 1984; Dubiel, 1989a; Dubiel, 1993). It ranges from more than 80 m thick to zero where it pinches out against the margins of the paleovalley (Stewart and others, 1972). Distinctive sedimentary features in the Monitor Butte include: 1) delta foreset beds; 2) thin, broad channels; and 3) contorted and slumped strata (Stewart and others, 1972; Dubiel and others, 1993). Large-scale scours at the base of the Monitor Butte in southeastern Utah cut out some or all of the underlying Shinarump Member (Stewart and others, 1972; Dubiel, 1994). The Monitor Butte has been interpreted as having been deposited in fluvial, lacustrine, lacustrine delta, and paludal environments (Stewart and others, 1972; Pierson, 1984; Dubiel, 1987).

The Moss Back Member is a sandstone unit that occurs above the Monitor Butte Member in southeastern Utah and above the Temple Mountain Member in the San Rafael Swell area (or above older rocks where the Monitor Butte, Temple Mountain, or Shinarump Members are not present) in a belt 80-120 km wide (Blakey and Gubitosa, 1983) in northern New Mexico, southwestern Colorado, and southeastern Utah (Figure 1). It ranges from 50 m thick in the White Canyon area of southern Utah to zero along the margins of the paleovalley (Stewart and others, 1972). The lower part of the Moss Back is characterized by large-scale trough and planar cross bedded, medium-grained sandstone with interbedded carbonate nodule and extrabasinal pebble conglomerates near the base of the unit, and the upper part is characterized by small- and large-scale trough and planar cross-bedded,
medium- to fine-grained sandstone (Stewart and others, 1972; Pavlak, 1979). The Moss Back Member has been interpreted to have been deposited in high- and low-sinuosity stream environments. Dubiel (1987) and Blakey and Gubitosa (1984) differ in their interpretations of the environment of deposition of the Moss Back Member. Blakey and Gubitosa (1984) interpret the sandstones in this unit as low-sinuosity, braided stream deposits, whereas Dubiel (1987) viewed them as having been deposited by high-sinuosity, meandering streams. However, Dubiel (1987) also took into account laterally adjacent levee and overbank deposits, which were ignored by Blakey and Gubitosa (1983, 1984). Pavlak (1979) interpreted the Moss Back in the San Rafael Swell area to have been deposited in high-, low-, and intermediate sinuosity streams with a progression from lower to higher sinuosity throughout deposition.

The Petrified Forest Member overlies the Moss Back and Monitor Butte Members. It consists of variegated lavender, white, red, and purple smectitic mudstone and sandstone, with minor carbonate-nodule conglomerate and black, organic-rich mudstone (Dubiel, 1987; Stewart and others, 1972). The Petrified Forest Member ranges from 45 m to 330 m thick and pinches out over the San Rafael Swell east of Monticello, UT, and north of Capitol Reef (O'Sullivan, 1975; Blakey and Gubitosa, 1984; Dubiel, 1987). Dubiel (1987) interpreted the Petrified Forest Member as high-sinuosity stream and associated levee, crevasse splay, and overbank/floodplain deposits. The Sonsela sandstone bed, a prominent conglomeratic sandstone unit in the middle of the Petrified Forest Member in eastern Arizona and western New Mexico is an exception, showing evidence of deposition in a low-
sinuosity, bed-load dominated environment (Deacon, 1990). Dubiel (1987) and Stewart and others (1972) recognized that much of the variegated coloration in the finer-grained portions of the Petrified Forest Member was produced by pedogenic alteration on the Chinle floodplains. Large-scale scour features up 10 m deep and filled by lateral-accretion and overbank deposits have also been recognized in the Petrified Forest Member in and around Petrified Forest National Park (Kraus and Middleton, 1987; Zuber, 1990).

**Distribution and taphonomy of fossil plants**

Plant fossils are found within channel (actively-filled and abandoned) and overbank (including crevasse splay, lacustrine delta, and paludal) deposits within the paleovalley fill sequence of the lower Chinle (Figure 2). A summary of the sedimentologic and taphonomic characteristics of plant-bearing units is shown in Figure 3. Transported gymnosperm wood fragments, including coalified branches and the large silicified trunks for which the formation is famous, are preserved in both high- and low-sinousity channel-fills in the Temple Mountain, Shinarump, Moss Back, and Petrified Forest Members (Figure 4). This material was introduced into the channels by cutbank erosion and channel migration and buried by bar migration and channel aggradation. In-place horsetail trunks and rhizomes and transported cycadeoid and conifer foliage are preserved as coalified compressions in carbonaceous, mudstone-filled abandoned channels in the Petrified Forest Member. In-place horsetail trunks and associated parautochthonous foliage are also preserved in crevasse splays and along the margins of overbank lacustrine deltas (Daugherty, 1941; Holt, 1947; Ash, 1972; Dubiel, 1987). These plants grew in areas characterized by high sedimentation rates and
Figure 3. Summary of sedimentologic and taphonomic characteristics of plant-bearing units (PBU's) in the Chinle Formation.
Figure 4. Typical fossil plants and their preservational modes. A, silicified logs in channel fill deposits, Sonsela sandstone, Petrified Forest National Park, AZ. B, cycadeoid foliage from paludal overbank deposits, Montior Butte Member, Fort Wingate, NM. C, coal seam from base of Monitor Butte Member, White Canyon, UT.
were continually buried during life by overbank sedimentation, a common preservational mode of fossil horsetails (Demko and Gastaldo, 1992; Gastaldo, 1992). Litter layers composed dominantly of coalified compressions of whole and partial cycadeoid (Figure 4), cycad, and fern foliage are preserved in paludal areas and lacustrine deltas in overbank environments in the Monitor Butte Member. This material, some of which may have been deciduously abcised (Ash, 1975b, 1991) was buried near the growth site of the parent plants by overbank sedimentation. *In situ* plants are also preserved in thin coal seams in the Monitor Butte Member (Dubiel, 1987) (Figure 4). Plant material was preserved in these mires by perennial maintenance of a high water table (Dubiel, 1983, 1994)

**Discussion and Conclusions**

The distribution and preservation of fossil plants in the lower Chinle Formation were controlled by sedimentological and near-surface geochemical conditions inherent to depositional settings within the incised-valley fill sequence. The abundance of plant fossils in the lower Chinle (Temple Mountain, Shinarump, Monitor Butte, Moss Back, and Petrified Forest Members), as compared to the upper Chinle (Owl Rock and Church Rock Members), is partly the result of deposition within aggrading fluvial and overbank systems confined in paleovalleys.

After the incision of the paleovalleys and a period of pedogenesis of the resulting land surface (represented by the mottled strata), the first evidence of aggradation is the lower conglomeratic sandstones of the Shinarump Member. These sandstones, confined to the lowest parts of the incised valleys in channel-form scours, preserve abundant silicified and coalified woody
material (Witkind, 1956, 1961; Phoenix, 1963; Witkind and Thaden, 1963; Davidson, 1967). The overlying sheet sandstones, which were confined to the paleovalleys but not to the deepest scours, are comparatively devoid of organic material. An extensive paleosol at the top of the Shinarump represents a period of landscape stability and little deposition within the paleovalleys, even though pedogenic and ichnologic features within the paleosol suggest fluctuating water tables (Dubiel, 1994).

The overlying Montitor Butte Member records continued aggradation within the paleovalleys, punctuated by episodes of degradation and incision. Lacustrine deposits in the Monitor Butte, including delta-front foresets as high as 25 m (Dubiel, 1983) and extensive overbank paludal deposits, including localized mires, indicate that water tables within the paleovalley were perennially high. However, large-scale scour surfaces within the Montior Butte Member, which in some places cut through the underlying Shinarump sandstones (Stewart and others, 1972), indicate that the overall aggradational sequence was interrupted by at least one period of incision. These scours, which represent inset paleovalleys within the larger paleovalley infill sequence, commonly have rotated slump blocks from the paleovalley walls in the base of their fill (Dubiel and others, 1993). The abundance of volcanic material, including tuffaceous sandstones and smectitic mudstones, in the Monitor Butte indicates a significant portion of sediment in these depositional environments came from extrabasinal sources, presumably wind-blown material from the contemporaneous volcanic arc to the west (Riggs and others, 1994). Fossil plants, especially coalified impressions of cycadaceous and fern foliage and in situ horsetail trunks, are abundant in
lacustrine and overbank paludal deposits, and coalified woody material is common in high-sinuosity channel deposits of the Monitor Butte. Most of the taxa from the Chinle flora have been described from assemblages preserved in the Monitor Butte Member (Daugherty, 1941; Ash, 1970-1989) (note that part of the "lower Petrified Forest Member" mentioned in some of these publications has been shown to be equivalent to the Monitor Butte Member; Dubiel and others, 1995).

The Moss Back Member is a channel-belt complex which infills another inset paleovalley, cut into the Monitor Butte and older units, within the larger-scale paleovalley infill sequence. Coalified woody material is abundant in small log jams in channel-lag deposits and as stranded detritus on the upper parts of point bar deposits. The Cottonwood paleovalley is filled entirely with Moss Back fluvial channel deposits. Thin overbank deposits are present laterally adjacent to the upper parts of the Moss Back, and are characterized by well-developed, calcareous, vertic palesols (Dubiel, 1994). The Cottonwood paleovalley and the Moss Back fluvial sandstones represent the last incision and infill event in the paleovalley infill sequence. Although the Moss Back is present only in southern and central Utah, distinctive fluvial sandstones in the Petrified Forest Member farther to the south, including the Sonsela sandstone in Arizona and New Mexico, could have been deposited in response to the same events. Deposits in the overlying Petrified Forest Member are similar in both areas, typified by thin, broad, high-sinuosity channel deposits and gray, purple, and red smectitic overbank mudstones with gleyed and vertic paleosols. Plant fossils are found only in isolated, areally restricted, abandoned channel deposits (Dubiel, 1994). The
Petrified Forest fluvial systems, and the rest of the Chinle Formation, were deposited under unconfined conditions—the relief created by the incision of the basal paleovalley system was completely buried.

The predominance of fossil plant assemblages in the lower part of the Chinle Formation, as compared to the dearth of fossil plants in the upper part, is due to their preservation within depositional environments in an incised valley system (Figure 5). Even though groundwater tables regionally were likely affected by seasonal fluctuations in recharge and level (Hasiotis and Mitchell, 1989; Dubiel and others, 1991), within the paleovalley water tables were perennially high, as they are in most modern alluvial valleys (Gallagher and Price, 1966; Runkle, 1985). Burial of the plant material within depositional environments in the paleovalleys (channels, splays, lakes, wetlands, and lacustrine deltas) increased its preservation potential because reducing conditions and low biological oxygen demand in these areas of high (near and at surface) water tables and groundwater discharge were conducive to low rates of decay. Foliar material buried in mud and silt was preserved as coalified compressions, some with unaltered cuticle. Woody material buried in channel and bar sandstones was preserved by early permineralization by silica (from devitrifying volcanic glass in the sandstone or stratigraphically-adjacent ash-rich mudstones) or as coalified compressions. The mineralization process was aided by groundwater flow through the sandstones after burial, when they acted as alluvial aquifers within the buried paleovalley sediments.
Figure 5. Schematic cross-section of a paleovalley during infill, showing sedimentologic and hydrologic conditions conducive to preservation of fossil plants, based on sedimentary facies, paleosols, and plant taphofacies in the lower part of the Chinle Formation. Environments and valley wall slopes are not to scale.
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Appendix C: Measured Stratigraphic Sections

Note: Locations of sections and plant assemblages not given in text may be obtained from the author.
324942
Newspaper Rock sandstone, Newspaper Rock
10.5 m

3.7 m sandstone, very fine, yellowish gray to grayish orange pink, small scale
trough cross beds, ripple cross lamination
**sharp contact**

4.2 m sandstone, very fine-fine, yellowish gray to grayish orange pink, ripple
cross lamination, small scale trough cross beds in basal scour, basal
lag of coalified logs, fines upward to very fine
**sharp, erosional contact (0.5-0.75 m relief)**

0.6 m mudstone, yellowish gray, massive, gley
**gradational contact**

>2.0 m mudstone, pale purple to grayish purple, massive, gley, lower purple
palesol, base of section

Graphic column in Appendix A.
324943
Newspaper Rock sandstone, east NPR Mesa
11.9 m

2.25 m sandstone, very fine-medium, yellowish gray, large scale trough cross beds 0.5 m, capped by small scale trough cross beds 0.25 m, mudchip conglomerate at base of small scale trough cross bed sets, large scale trough cross beds medium-fine, small scale trough cross beds fine-very fine

  sharp contact

0.5 m sandstone, very fine-fine, yellowish gray, ripple cross lamination, small scale trough cross beds, parallel lamination

  sharp contact

0.5 m sandstone, very fine-fine, yellowish gray, ripple cross lamination 0.4 m, overlain by small trough cross beds and parallel lamination

  sharp contact

2.0 m sandstone, very fine-medium, yellowish gray, interbedded small scale trough cross bed sets (very fine-fine) and large scale trough cross bed sets (medium-fine), sets 0.2-0.3 m, climbing ripple cross lamination

  sharp contact

0.4 m sandstone, fine-medium, yellowish gray, small scale trough cross beds, ripple cross lamination

  sharp contact

1.5 m sandstone, fine-medium, yellowish gray, small and large scale trough bed sets 0.2-0.5 m, scour and fill 0.5 m, some sets have basal mudchip conglomerate

  sharp contact

1.0 m sandstone, fine-medium, yellowish gray, medium scale trough cross bed sets 0.2-0.5 m, well-cemented

  sharp contact

2.1 m sandstone, medium-fine, yellowish gray, fines up to fine, large scale trough cross beds, poorly preserved plant material on bedding planes

  sharp contact

0.25 m conglomerate, light olive gray, pebble-sized mudchip clasts, base of Newspaper Rock sandstone

  sharp, erosional contact

0.4 m mudstone, light olive gray, massive, gley

  gradational contact

>1.0 m mudstone, very dusky purple, massive, lower purple paleosol, base of section
2.0 m mudstone, grayish red purple with light greenish gray gley spots, massive, upper purple paleosol

gradational contact

0.9 m mudstone, grayish red with light greenish gray gley spots, massive, smectitic, Fe concretions 0.2-0.3 cm, slickensides

gradational contact

0.8 m muddy siltstone, light olive gray and grayish red mottled, slickensides, massive

gradational contact

0.5 m silty sandstone, very fine, light olive gray and grayish red mottled, massive

sharp contact

0.4 m muddy siltstone, light olive gray and grayish red mottled, slickensides, massive

gradational contact

0.7 m silty sandstone, very fine, light olive gray and grayish red mottled, massive

sharp contact

0.202 m sandstone, very fine-fine, mudcracks, crayfish burrows 5-13 cm diam, back-filled meniscate burrows 0.8 cm, simple vertical burrows (bee-type) 0.5 cm diam, small branching burrows 0.1 cm diam, ripples, load structures, pinches out laterally:

0.45 m ripple cross lamination, small channels 0.2-0.3 m deep,
1.5 m wide, basal mudchip conlomerate, parallel laminaion

0.4 m ripple cross lamination

0.12 m parallel lamination

0.3 m ripple cross lamination, mudchip conglomerate

0.23 m ripple cross lamination, pebble-sized mudschip conglomerate

0.4 m ripple cross lamination

0.12 m ripple cross lamination

sharp, erosional contact

>2.0 m mudstone, medium bluish gray to light bluish gray and light olive ray to yellowish gray mottled, massive, slickensides, lower purple paleosol, base of section
324946
Far Tepees
6.3 m

>2.0 m silty mudstone, pale purple and yellowish gray mottled, massive,
  upper purple paleosol
  **sharp contact**
1.55 m mudstone, grayish red with very light gray gleys, flaky fracture,
  massive, slickensides, *Scyenia* burrows, upper red paleosol
  **sharp contact**
0.75 m silty mudstone, grayish purple to very dusky purple and pinkish gray
  mottled, massive
  **sharp contact**
0.5 m mudstone, grayish red, massive, slickensides
  **gradational contact**
>2.0 m mudstone, grayish blue, massive, lower purple paleosol, base of
  section

Graphic column in Appendix A.
324947
Candy Striped Tepees
18.5 m

>2.0 m silty mudstone, grayish purple with yellowish gray mottles, massive, slickensides, upper purple paleosol
  sharp contact
1.0 m mudstone, grayish red, massive, slickensides, Scoyenia burrows, roots, upper red paleosol
  sharp contact
0.5 m mudstone, grayish red, massive
  gradational contact
0.7 m sandstone, very fine, light olive gray, ripple cross lamination
  sharp contact
0.3 m interbedded mudstone and sandstone, very fine, pale red to grayish red, laminated
  gradational contact
0.7 m siltstone, light olive gray, laminated
  sharp contact
0.25 m interbedded mudstone and sandstone, very fine, pale red to grayish red, laminated
  gradational contact
0.4 m siltstone, light olive gray, laminated
  sharp contact
0.2 m interbedded mudstone and sandstone, very fine, pale red to grayish red, laminated
  gradational contact
0.5 m siltstone, light olive gray, laminated
  sharp contact
0.2 m mudstone, pale red to grayish red, massive, flaky fracture
  gradational contact
0.8 m siltstone, light olive gray, laminated
  sharp contact
0.2 m mudstone, pale red to grayish red, massive, flaky fracture
  gradational contact
0.75 m siltstone, light olive gray, laminated
  sharp contact
0.4 m mudstone, pale red to grayish red, massive, flaky fracture
  gradational contact
0.5 m siltstone, light olive gray, laminated
  sharp contact
0.3 m mudstone, pale red to grayish red, massive, flaky fracture
gradational contact

0.6 m siltstone, light olive gray, laminated
sharp contact

0.2 m mudstone, pale red to grayish red, massive, flaky fracture
gradational contact

0.6 m siltstone, light olive gray, laminated
sharp contact

0.2 m mudstone, pale red to grayish red, massive, flaky fracture
gradational contact

2.2 m muddy siltstone, light olive gray, plant detritus
gradational contact

4.0 m interbedded mudstone and siltstone, light gray to medium light gray,
laminated, abundant coalified logs, carbonized roots, plant material
sharp, erosional contact

>1.0 m mudstone, grayish blue with light gray mottles, massive, Scoyenia
burrows, lower purple paleosol, base of section

Graphic column in Appendix A.
Newspaper Rock Mesa section
9.45 m

4.7 m sandstone, very fine-fine, pale yellow, ripple cross lamination, micaceous along bedding planes
sharp contact

1.45 m sandstone, very fine-fine, pale yellow, parallel and ripple cross lamination
sharp contact

0.5 m sandstone, very fine-fine, pale yellow, parallel and ripple cross lamination
sharp contact

0.1 m granule conglomerate, very fine-fine matrix, matrix supported
sharp contact

0.7 m sandstone, very fine-fine, parallel and ripple cross lamination, micaceous along bedding planes
sharp contact

0.8 m sandstone, very fine-fine, parallel and ripple cross lamination, micaceous along bedding planes
sharp contact

1.2 m sandstone, very fine-fine, parallel and ripple cross lamination, micaceous along bedding planes
sharp contact

0.8 m silty sandstone, very fine-fine, light gray, micaceous, comminuted plant material, soft sediment deformation structures in top 0.4 m
gradational contact

0.2 m conglomerate, grayish blue to yellowish gray, mudchip clasts, base of Newspaper Rock sandstone
sharp, erosional contact

0.8 m mudstone, light brownish gray, massive, slickensides
sharp contact

0.8 m muddy siltstone, dark reddish gray with light greenish gray gley spots, Fe nodules
gradational contact

0.5 m siltstone, graysih red, massive
gradational contact

0.7 m mudstone, moderate red, massive, slickensides, grades up to silty mudstone, reddish gray with light greenish gray gley spots, massive
sharp contact
1.0 m silty sandstone, fine-medium, micaceous, mudchips, moderate red and light greenish gray mottled, fines up to sandy siltstone, base of section
2.2 m mudstone, grayish purple and light gray mottled, massive, smectitic, upper purple paleosol
gradational contact
3.6 m mudstone, weak red with white gley spots, massive, rootlets, patchy silty layers 0.5 m, large cyclindrical burrows (4-5 cm long), Scoyenia, upper red paleosol sharp contact
0.1 m silty sandstone, very fine, light gray, ripple cross lamination, parallel lamination sharp contact
0.1 m silty mudstone, weak red, massive, hackly fracture sharp contact
1.0 m silty sandstone, very fine, gray, laminated, fines up to siltstone sharp contact
0.3 m silty sandstone, fine, light gray, climbing ripple cross lamination, small scale trough cross beds, vertical burrows 1 cm diam sharp contact
0.18 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus gradational contact
0.20 m silty sandstone, fine, light gray, climbing ripple cross lamination, small scale trough cross beds sharp contact
0.3 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus gradational contact
0.5 m silty sandstone, fine, light gray, climbing ripple cross lamination, small scale trough cross beds sharp contact
0.2 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus gradational contact
0.6 m silty sandstone, fine, light gray, climbing ripple cross lamination, small scale trough cross beds sharp contact
0.18 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
0.9 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds
sharp contact
0.39 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
0.6 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds
sharp contact
0.3 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
0.4 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds
sharp contact
0.27 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
0.37 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds
sharp contact
0.3 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
0.54 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds
sharp contact
0.4 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
0.6 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds
sharp contact
0.15 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
gradational contact
1.13 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds

**sharp contact**

0.25 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
628941
Sonsela at South Blue Mesa, levee
31.6 m

2.5 m interbedded sandstone and conglomeratic sandstone, medium, chert, mudchip and carbonate nodule clasts 2-10 cm, medium coarse matrix, conglomerate beds 0.5 m, sandstone beds 1.0 m, small-lage scale trough cross beds; Flattops sandstone #1?
sharp, erosional contact

1.5 m mudstone, light gray and purplish gray mottled, carbonate nodules 3-5 cm, poorly preserved silicified roots
gradational contact

0.4 m mudstone, light gray, massive, slickensides
gradational contact

1.0 m mudstone, dark brownish red, massive, mukkara, carbonate nodules 2-7 cm
gradational contact

1.7 m mudstone, dark purplish red and light gray mottled, massive, light gray halos around roots
gradational contact

1.3 m mudstone, light gray and grayish red mottled, massive, fine mica flakes (tuff?)
gradational contact

2.7 m silty sandstone, very fine-fine, light gray with purple mottles, grades up to silty mudstone, light purplish red, poorly preserved silicified roots
gradational contact

4.7 m interbedded sandstone and conglomerate, fine-medium, light gray, chert and volcanic clasts 2-7 cm, medium scale trough cross beds, top of Sonsela sandstone
gradational contact

0.4 m conglomerate, medium-coarse matrix, chert, mudchip and volcanic clasts 3-7 cm
sharp, erosional contact

1.8 m mudstone, dark brownish red with light gray mottles, hackly fracture, grades up to reddish gray mudstone
gradational contact

1.2 m silty mudstone, light reddish brown with light gray mottles along roots, massive, hackly fracture, grades up to mudstone
gradational contact
1.13 m silty sandstone, very fine, light gray, climbing ripple cross lamination, small scale trough cross beds

**sharp contact**

0.25 m silty mudstone, greenish gray, laminated, slickensides, plant macrodetritus
South Blue Mesa, Petrified Forest NP
628941

<table>
<thead>
<tr>
<th>m</th>
<th>point bars</th>
<th>Flattops sandstone</th>
</tr>
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<tbody>
<tr>
<td>31.6</td>
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<td>15</td>
<td>overbank paleosol</td>
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<tr>
<td>10</td>
<td>overbank vertisol</td>
<td>Flattops sandstone complex</td>
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<td></td>
<td>abandoned channel</td>
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<td>mid-channel bars</td>
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<td>overbank paleosols</td>
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<td>levee</td>
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<tr>
<td></td>
<td>lateral bar</td>
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</tbody>
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ns allign marcs congl
628942
Sonsela at South Blue Mesa, channel
34.2 m

3.0 m sandstone, fine, well cemented, mudchip conglomerate interbeds, medium scale trough cross beds, Flattops sandstone #1?
sharp contact

0.3-0.5 m conglomerate, carbonate nodule and unionid clams, clams convex upward, single valves, nodules 0.2-6 cm
sharp, erosional contact

3.7 m mudstone, light olive gray with grayish purple mottles, massive, slickensides
gradational contact

2.5 m mudstone, dark reddish brown with light olive gray mottles, flaky fracture, rootlets and root halos
gradational contact

1.4 m mudstone, light olive gray, laminated, laterally equivalent to small channel sandstone, fine, medium scale trough cross beds and parallel lamination, tuffaceous
gradational contact

2.6 m mudstone, brownish red with light gray mottles, carbonate nodules 3-5 cm in lower 2 m, light gray root halos, mukkara, rootlets
gradational contact

1.4 m mudstone, light gray and reddish purple mottled, massive, blocky fracture
gradational contact

1.7 m silty mudstone, light gray, micaceous, massive, grades up to mudstone
sharp contact

0.7-1.5 m sandstone, fine, tannish gray, medium scale trough and tabular cross beds, biotite flakes, backfilled chambers and burrows (insect burrow bed)
sharp contact

9.0 m sandstone with interbedded conglomeratic sandstone and conglomerate, medium-coarse, chert grains, muscovite and biotite flakes, chert and volcanic clasts 1-8 cm, matrix and clast supported conglomerate layers 1-2 m, sandstone layers 1-4 m, conglomeratic sandstone layers 0.5-1 m, basal mudchip conglomerate, large scale trough cross beds, overturned cross beds, large petrified logs, top of Sonsela sandstone
sharp, erosional contact
0.8 m mudstone, dark grayish red with light gray mottles, massive, slickensides  
gradational contact

0.8 m sandy siltstone, light grayish red with gray mottles, micaceous, disrupted lamination
gradational contact

1.0 m silty sandstone, fine, light grayish red with light gray mottles, muscovite and biotite flakes, laminated
gradational contact

2.0 m sandstone, medium-coarse, light gray, medium to large scale trough cross beds, micaceous, tuffaceous
sharp, erosional contact

0.3 m mudstone, light gray, massive, slickensides  
gradational contact

0.9 m mudstone, dark grayish purple with light gray mottles, light gray halos around roots, slickensides
gradational contact

1.0 m mudstone, light olive gray with purple mottles, massive, slickensides  
gradational contact

1.5 m silty mudstone, dark grayish purple with large olive gray mottles, massive, hackly fracture
gradational contact

1.5 m silty mudstone, dark purplish red with gray mottles, shaley bedding, grades up into sily mudstone, gray with purple mottles, massive
gradational contact

0.3 m silty mudstone, light gray with pale purple mottles, fine muscovite and biotite flakes (tuff?)
sharp contact

0.4 m silty sandstone, very fine-fine, reddish brown and gray mottled, laminated, muscovite and biotite flakes (tuff?)
sharp contact

1.9 m sandstone, medium, light gray, biotite flakes, medium to large scale trough cross beds, tuffaceous, base of section
**Sonsela and Flattops sandstones, South Blue Mesa**

**Petrified Forest NP**

<table>
<thead>
<tr>
<th>Channel and Point Bars</th>
<th>Flattops Sandstone</th>
</tr>
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<tbody>
<tr>
<td>Proximal Overbank Paleosol</td>
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<tr>
<td>Distal Overbank Paleosol</td>
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<tr>
<td>Abandoned Channel</td>
<td></td>
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<tr>
<td>Distal Overbank Vertisol</td>
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<tr>
<td>Proximal Overbank Paleosol</td>
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<tr>
<td>Crevasse Splay</td>
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</tbody>
</table>

![Diagram of stratigraphy](image-url)
mid-channel bars
Sonsela/Rainbow sandstone complex
proximal overbank gleysols
abandoned channel
levee

mid-channel bars
Sonsela/Rainbow sandstone complex
proximal overbank gleysols
abandoned channel
levee

mix of fine to coarse congl
628943
South Blue Mesa, abandoned channel with macroplants
24.6 m

1.5 m sandstone, fine-medium, light gray, micaceous, medium to large scale
trough cross beds, Flattops sandstone #1?
sharp contact
0.1-0.2 m conglomerate, coarse matrix, dark reddish brown, chert granule and
carbonate nodule clasts 0.1-0.2 cm, small scale trough cross beds
sharp, erosional contact
1.0 m mudstone, dark grayish purple with light gray mottles, massive
gradational contact
1.5 m mudstone, reddish brown and light gray mottled
sharp contact
3.2 m mudstone, light reddish brown and light gray mottled, grades up to red
mudstone
sharp contact
0.1-0.15 m sandstone, fine, light gray, red mudstone interbeds
sharp contact
1.8 m mudstone, brownish red and light gray mottled, massive, slickensides
sharp contact
0.3-0.4 m sandstone, very fine-fine, light gray, well cemented, small scale
trough cross beds, abundant backfilled chambers and burrows (insect
burrow bed)
sharp contact
1.9 m mudstone, dark brownish red, massive, carbonate nodules 4-5cm,
mukkara
gradational
2.6 m mudstone, dark reddish purple with light gray mottles, massive,
slickensides, laterally equivalent to mudstone, dark reddish brown,
mukkara, carbonate nodules 3-5 cm
gradational contact
1.8 m mudstone, olive gray, massive, blocky fracture
gradational contact
3.0 m mudstone, black to dark gray, carbonaceous, abundant coalified plant
material
sharp, interfingering
5.5 m sandstone, medium, light gray, sparse chert pebble conglomerate
layers, medium scale trough cross beds, overturned cross beds, fines
upward to fine with tabular cross beds, top of Sonsela, base of section
South Blue Mesa, Petrified Forest NP
628943

<table>
<thead>
<tr>
<th>24.3</th>
<th>point bars</th>
<th>Flattops sandstone</th>
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</thead>
<tbody>
<tr>
<td>20</td>
<td>overbank paleosols</td>
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<td>15</td>
<td>distal splay overbank paleosol</td>
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<td>distal overbank vertisols</td>
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<td>abandoned channel</td>
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<td>10</td>
<td>lateral bars</td>
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<td>5</td>
<td>Sonsela/Rainbow sandstone complex</td>
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<td>m all the way congr!</td>
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</tbody>
</table>
Wild Horse Draw, Sonsela sandstone to Painted Desert sandstone

110 m

8.5 m sandstone, fine-medium, light gray to reddish gray, weathers tan to brown, large scale trough cross bed sets 0.5-1 m, parallel and ripple cross lamination, scour and fill, lateral accretion surfaces, mudchip and carbonate nodule conglomerate at base 0.4 m, Painted Desert sandstone

shar p, erosional contact

6.0 m mudstone, brownish red with light gray gley spots, carbonate nodules 3-5 cm, massive, slickensides

sharp contact

3.0 m muddy sandstone, coarse, reddish brown, mud chip and carbonate nodule clasts

sharp contact

0.7 m silty mudstone and siltstone, brownish red with light gray gley spots, carbonate nodules 0.2-0.3 cm, massive

gradational contact

3.4 m mudstone, dark red, carbonate nodules 0.2-0.3 cm, massive, slickensides

gradational contact

1.5 m siltstone, grayish red with light gray gley spots, carbonate nodules 0.2-0.3 cm

gradational contact

4.0 m sandstone, fine, reddish gray, weathers grayish brown, medium scale trough cross beds, ripple cross lamination

gradational contact

0.3 m conglomerate, carbonate nodule and mudchip clasts, red to reddish gray, red mudchip granule matrix

sharp, erosional contact

5.4 m mudstone, dark grayish red, light gray gley spots, large Scoyenia, carbonate nodules 0.2-0.3 cm, massive

gradational contact

0.5 m mudstone, brownish red, Scoyenia, carbonate nodules 0.3-0.5 cm, massive

gradational contact

3.0 m mudstone, dark red with light gray gley spots, gley halos around rootlets, Scoyenia, massive, slickensides

gradational contact
1.0 m mudstone, brownish red with light gray gley spots, *Scyenia*, massive, slickensides
   **gradational contact**
7.5 m mudstone, dark brownish red with light gray gley spots, carbonate nodules 0.2-0.3 cm, massive, slickensides
   **gradational contact**
2.6 m mudstone, dark brownish red, mukkara, carbonate nodules 2-10 cm, massive, slickensides
   **gradational contact**
1.0 m mudstone, dark brownish red with light red mottles and light gray gley spots, roots, massive
   **gradational contact**
1.7 m mudstone, dark purplish red with light gray gley spots, massive, slickensides
   **gradational contact**
1.0 m mudstone, olive gray, massive
   **gradational contact**
0.8 m mudstone with silty laminations, medium to light gray, carbonized roots
   **sharp contact**
6.0 m sandstone, fine, light grayish red, weathers tan and dark brown, well cemented, large and medium scale trough cross beds, lateral accretion surfaces, interbedded carbonate nodule conglomerate lenses
   **sharp contact**
0-0.5 m conglomerate, carbonate nodule clasts 0.2-1.5 cm
   **sharp contact**
2.0 m muddy sandstone, coarse, grayish red, mudchip clasts
   **sharp contact**
2.5 m sandstone, fine, light reddish gray, weathers dark reddish brown, large scale trough and tabular cross beds, horizontal burrows, pinches out to east
   **sharp contact**
0.3 m conglomerate, carbonate nodule and chert granule, dark reddish brown, clasts 1-2 cm
   **sharp contact**
1.6 m mudstone, dark reddish brown, mukkara, carbonate nodules 0.2-0.3 cm, massive
   **gradational contact**
4.5 m mudstone, brownish red with light gray mottles, carbonate nodules 2-7 cm, massive
gradational contact

2.5 m mudstone, dark brownish red, massive

sharp contact

2.5 m mudstone, dark purplish red, carbonate nodules 2-5 cm, top contains abundant whitish carbonate nodules

sharp contact

1.0-2.5 m interbedded sandstone and conglomerate, light gray and grayish brown, mudchip, unionid bivalve, and carbonate nodule clasts, medium scale trough cross beds, low angle inclined bedding, scour and fill, pinches out to east, top of Sonsela sandstone

sharp, erosional contact

3.3 m silty mudstone, brownish red with light gray mottles, discontinuous carbonate layers 3-5 cm, micaceous

gradational contact

2.8 m mudstone, dark reddish purple with light gray mottles, carbonate nodules 2-15 cm, coalesced nodules

gradational contact

1.5 m mudstone, light brownish red with gray mottles, carbonate nodules 3-5 cm, grades up to dark brownish red

gradational contact

2.0 m silty mudstone, light gray, laminated, very fine mica, rootlets

gradational contact

3.0 m interbedded silty sandstone, very fine, and sandstone, fine-medium, light gray, silty beds 7-10 cm, sandstone beds 0.4 m, gently dipping cross lamination

gradational contact

0.6 m mudstone, light gray, laminated

sharp contact

2.3 m sandstone, medium, light gray, biotite and muscovite flakes, comminuted plant material, parallel and gently dipping lamination

gradational contact

3.0 m interbedded conglomerate and conglomeratic sandstone, fine-medium, light brown to dark reddish brown, chert granule matrix, carbonate nodule, unionid bivalve, bones, petrified wood, medium and large scale trough cross beds, ripple cross lamination

sharp contact

3.0 m sandstone, medium-coarse, light tannish brown, interbedded mudchip conglomerate up to cobble size, medium and large scale trough cross beds

gradational contact
0.7-1.5 m conglomerate, coarse matrix, grayish brown to dark brown, carbonate nodule and chert clasts up to 8 cm, unionid bivalves, medium scale trough cross beds, base of Sonsela sandstone

sharp, erosional contact

4.2 m mudstone, dark brownish red with light gray mottles, carbonate nodules 0.2-0.3 cm, slickensides

gradational contact

1.0 m mudstone, dark grayish purple with light gray gley spots, carbonate nodules 0.2-0.3 cm, massive

gradational contact

2.4 m mudstone, dark purplish red with light gray mottles, carbonate nodules 3-5 cm, massive

gradational contact

1.0 m mudstone, dark purplish brown with light gray mottles, pelloidal fabric, massive, slickensides

gradational contact

1.5 m mudstone, dark reddish purple with light purple mottles, massive, base of section
### Wild Horse Draw, Petrified Forest NP

<table>
<thead>
<tr>
<th>Channel and Point Bars</th>
<th>Painted Desert Sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distal Overbank Paleosols</td>
<td></td>
</tr>
<tr>
<td>Splay</td>
<td></td>
</tr>
<tr>
<td>Channel</td>
<td></td>
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<tr>
<td>Distal Overbank Paleosols</td>
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</tbody>
</table>

**Diagram Notes:**
- m: meters
- 629941

**Legend:**
- Painted Desert Sandstone
- Distal Overbank Paleosols
- Channel and Point Bars
- Splay
overbank paleosols

distal overbank vertisols

proximal overbank paleosols

channel and point bars

Painted Desert sandstone
channel

distal overbank vertisol

distal overbank paleosols

lateral and mid-channel bars

distal overbank sandstone complex

Sonsela/Rainbow sandstone complex

channel
distal overbank paleosol

levee and splay deposits

Sonsela/Rainbow sandstone complex

mid-channel bars

distal overbank paleosols
Rainbow sandstone to Flattops sandstone #1, north of old RT 180
54 m

9.0 m sandstone, medium-coarse, tannish gray, medium-large scale trough cross beds, top of Flattops sandstone #1
**sharp contact**

2.3 m interbedded sandstone and conglomeratic sandstone: sandstone, medium-coarse, brownish gray, and conglomeratic sandstone, chert pebbles, carbonate nodules, mudstone and sandstone rip-up clasts, large scale trough cross beds
**sharp contact**

0.7 m sandstone, medium-coarse, light brownish gray, medium scale trough cross beds, comminuted plant material on bedding planes
**sharp contact**

0-0.3 m conglomerate, carbonate nodule, coarse sand to 2 cm clasts
**sharp, erosional contact**

2.0 m sandstone, fine-medium, brown, conglomerate lenses: mudchip up to large cobbles, carbonate nodules 0.5 cm; base of Flattops sandstone #1
**sharp, erosional contact**

2.5 m silty mudstone, brownish red, carbonate nodules 0.5 cm, slickensides
**gradational contact**

1.9 m mudstone, olive gray, reddish mudstone interbeds, carbonate nodules 3-5 cm, Fe-replaced roots
**gradational contact**

0.9 m mudstone, dark brownish red, dark gray gley spots, hackly fracture, carbonate nodules 0.5 cm, slickensides
**gradational contact**

2.2 m mudstone, brownish red, carbonate nodules 0.5 cm
**gradational contact**

2.0 m mudstone, brownish red and gray mottled, smectitic, massive, carbonate nodules 3-5 cm, mukkara, grades up from gray to reddish gray
**gradational contact**

0.5 m shaley mudstone, grayish to reddish brown
**sharp contact**

1.9 m sandstone, fine-medium, smectitic, biotite and muscovite flakes (tuff?), medium scale trough cross beds, top contains discontinuous carbonate nodule conglomerate (0-0.6m); top of Rainbow sandstone
**sharp contact**
1.2 m mudstone, reddish brown and light gray mottled, slickensides

*gradational contact*

1.7 m mudstone, brownish red, brownish gray gley spots, massive, bottom 1 m contains carbonate nodules, nodules 0.5 cm at base, 1-2 cm at top, nodules fill pedogenic cracks

*gradational contact*

0.8 m mudstone, brownish red, light gray gley spots, massive, hackly fracture

*gradational contact*

2.8 m sandstone, fine-medium, medium-coarse biotite and muscovite flakes, large-medium scale trough cross beds, carbonate nodule lag at base, fines upward to light gray siltstone

*sharp contact*

0.8 m mudstone, reddish purple, abundant carbonate nodules 0.5 cm *

*gradational contact*

1.0 m mudstone, dark reddish purple, massive, *Scyenia*, carbonate nodules 1-2 cm, vertical burrows 1-2 mm diameter, rootlets with gley halos, slickensides *

*gradational contact*

0.7 m mudstone, gray, massive, slickensides *

*gradational contact*

0.9 m mudstone, reddish brown, light gray gley spots, rootlets with light gray gley halos *

*above 3.4 m * laterally equivalent to:

0.3 mudstone, light gray, massive

*gradational contact*

0.3 mudstone, dark grayish purple, light gray gley spots, massive, slickensides

*gradational contact*

2.8 mudstone, light olive gray and light reddish brown mottled, massive, dark reddish brown mottles around rootlets, grades up onto purplish gray and gray mottled mudstone

*sharp contact*

0.7 m interbedded sandstone and conglomerate, medium-coarse, mudchip clasts up to 7 cm, chert clasts, petrified wood 0.5-1 cm, top is rootworked

*sharp, erosional contact*

1.0 m mudstone, reddish brown and light olive gray mottled, massive, hackly fracture, slickensides, siltier towards top

*gradational contact*
3.6 m mudstone with silty interbeds (5-10 cm) in upper 1.5 m, rootlets with reddish brown halos

*gradational contact*

0.75 m silty sandstone, very fine-fine, reddish brown and medium gray mottled, micaceous (fine), massive but with some patchy bedding (pedoturbated)

*gradational contact*

0.6 m sandy siltstone, very fine, medium to light gray, laminated, biotite and muscovite flakes, flat mudchips 0.5 cm, rootlets with reddish brown halos

*gradational contact*

3.5 m interbedded sandstone and conglomerate, medium-coarse, light gray, chert, volcanic rock and mudchip clasts 5-15 cm, coarsens upward (more conglomerate), large petrified logs (Rainbow Forest)

*sharp, erosional contact*

5.0 m mudstone, purplish gray and purple mottled, light olive gray gley mottles, rootlets, Fe nodules 0.5 cm, slickensides

*sharp contact*

2.3 m sandstone, fine-medium, micaceous (tuff?), large to small scale trough cross beds, poorly preserved silicified roots; base of Rainbow sandstone

*sharp contact*

0.5 m mudstone, brownish red, massive, hackly fracture; base of section
Rainbow and Flattops sandstones, Rainbow Forest, Petrified Forest NP

Flattops sandstone

point bars and channel deposits

overbank paleosols

distal overbank vertisol

abandoned channel

channel

overbank paleosols

Sonsela/Rainbow sandstone complex
overbank paleosol
lateral bars
overbank paleosols
crevasse splay
proximal overbank paleosols
levee
mid-channel bars
Sonsela/Rainbow sandstone complex
proximal overbank gleysols
crevasse splay
overbank paleosol
2.0 m conglomeratic sandstone, medium-coarse, chert pebble clasts, large scale trough cross beds, large petrified logs (Rainbow Forest)
sharp contact

3.5 m silty sandstone, very fine-fine, light gray and purple mottled, large and medium scale trough cross beds
sharp contact

3.4 m conglomeratic sandstone, coarse, light gray, chert and volcanic clasts up to 10 cm, tuffaceous, large petrified logs (Rainbow Forest)
sharp contact

0.25 m conglomeratic sandstone, coarse-granule, dark greenish brown, angular granule-sized chert grains, pebble-sized red chert and quartz clasts
sharp contact

2.2 m silty sandstone, fine, micaceous, grades upward into sandstone, medium, micaceous (tuff?), large scale trough cross beds
sharp contact

4.0 m PLANT-BEARING UNIT

0.4 m carbonaceous mudstone with macroplant material
0.2 m sandstone, fine, with carbonaceous mudstone and plant material laminations
0.4 m siltstone with abundant macroplant material
0.2 m sandstone, fine, with carbonaceous mudstone and plant material laminations
0.4 m sandstone, fine, interbedded with carbonaceous mudstone
1.4 m sandstone, fine-medium, interbedded with carbonaceous mudstone
1.0 m sandstone, fine-medium, brown, muscovite flakes, laminated and small-scale trough cross beds
gradational, interfingering contact

2.5 m mudstone, brownish red to reddish purple mottled, massive, rootlets, slickensides
sharp contact

0.9 m silty mudstone, reddish brown, gley spots, rootlets
gradational contact

1.5 m sandstone, medium, reddish gray, micaceous (tuff?), medium to large scale trough cross beds, base of section
Rainbow sandstone, Giant Logs area
Petrified Forest NP

626942

lateral and mid-channel bars

lateral bar
abandoned channel
overbank paleosols
lateral bar

Sonsela/Rainbow sandstone complex
626943
Rainbow sandstone near bedded plant material
11.9 m

2.0 m interbedded silty sandstone and conglomeratic sandstone, fine-medium, chert clasts, coarse conglomeratic sandstone lenses, large petrified logs (Rainbow Forest)
gradational contact

2.6 m conglomeratic sandstone, coarse, small to large scale trough cross beds, large petrified logs (Rainbow Forest)
gradational contact

0.6 sandstone, medium, mudchip conglomerate, rare quartz pebbles, large scale trough cross beds
gradational contact

1.3 m sandstone, medium, light gray, sparse chert pebble conglomerate
gradational contact

0.3 m mudchip conglomerate, purplish gray mottled
sharp, erosional contact

1.2 m mudstone, purplish gray and gray mottled, massive
gradational contact

0.8 m mudstone, light gray with purple mottles, purple halos around rootlets
sharp contact

0.6 m mudstone, reddish purple, gray mottles, hackly fracture
sharp contact

2.5 m sandstone, fine-medium, gray with reddish mottles, micaceous (tuff?), fines upward to very fine; base of section
Rainbow sandstone, Giant Logs area
626943

mid-channel bars

lateral bar

proximal overbank gleysols

levee

Sonsela/Rainbow sandstone complex
5.5 m mudstone, light purplish gray, massive, slickensides, carbonate nodules 2-5 cm
gradational contact
0.4 m mudstone, brownish red with light gray mottles, massive, carbonate nodules 0.5-2 cm, rootlets
gradational contact
1.5 m mudstone, dark brownish red, massive, slickensides, carbonate nodules 0.5-2 cm
gradational contact
1.5 m mudstone, dark grayish purple with light gray mottles, massive sharp contact
2.6 m sandstone, fine-medium, light gray to light purplish gray, tuffaceous, laminated, low angle cross stratification sharp contact
0.15-0.5 m conglomerate, carbonate nodule clasts 2-10 cm, abundant bone fragments sharp contact
1.4 m mudstone, brownish red with light ray mottles, massive, carbonate nodules 2-10 cm, coalesced sharp contact
1.2 m silty mudstone, brownish red with light gray mottles, carbonate nodules 2-3 cm, carbonate layer in upper part 3-4 cm sharp contact
2.0 m sandstone, medium, tuffaceous, medium to large scale trough cross beds sharp, erosional contact (2 m relief)
5.0 m mudstone, grayish purple with light gray mottles, massive, grades up to dark grayish red with light gray mottles, root halos gradational contact
>1.5 m sandstone, medium-coarse, grayish purple mudstone interbeds 0.1-0.2 m, small to medium scale trough cross beds, low angle cross stratification, large silicified logs (Long Logs), base of section
Long Logs, Petrified Forest NP

20

Petrified Forest Member

15

channel

channel

10

overbank paleosols

overbank paleosols

* Sonsela/Rainbow sandstone complex

5

channel

overbank paleosols

0

m

m s t i f f a m a s c o n g l
>4.8 m conglomeratic sandstone, medium-coarse, light gray to tannish brown, carbonate nodule, mudchip, and chert clasts up to 5 cm, medium to large scale trough cross beds, lateral accretion surfaces, fines up (less conglomerate)

sharp contact

0.3 m conglomerate, carbonate nodule and mudchip clasts up to 8 cm, base of Flattops sandstone

sharp, erosional contact

2.3 m mudstone, dark reddish gray with light gray mottles, carbonate nodules 2-3 cm in upper 0.2 m

gradational contact

1.0 m sandstone, fine, light gray to purplish gray, basal carbonate nodule conglomerate 0.1 m

sharp contact

1.8 m mudstone, dark reddish purple with light gray mottles, massive, carbonate nodules 2-3 cm

gradational contact

2.0 m interbedded silty sandstone and silty mudstone, fine, reddish brown, laminated, micaceous (tuff?), tuffaceous sandstone interbeds, ripple cross laminated, fines up to mudstone

gradational contact

1.8 m sandstone, fine, light gray to light purplish gray, basal granule and mudchip conglomerate, grades laterally into siltstone, light reddish brown

sharp contact

1.4 m mudstone, dark grayish purple with light gray mottles, massive, carbonate nodules 2-3 cm, discontinuous coalesced carbonate nodule layers at base 2-5 cm, root halos

gradational contact (locally sharp)

2.1 m silty mudstone, light purplish gray and light gray mottled

gradational contact

2.0 m silty mudstone, light purplish gray and light gray mottled, grades up to dark brownish red, carbonate nodules 0.2-0.5 cm, slickensides

sharp contact

1.3 m sandstone, medium, light ray to light purplish gray, large scale trough cross beds, top of Rainbow sandstone

sharp contact
6.2 m sandstone, fine-medium, light gray, conglomeratic interbeds, chert, quartz, volcanic rock clasts, tuffaceous, large scale trough cross beds, large silicified logs at base (Long Logs), base of Rainbow sandstone

**sharp, erosional contact**

0.6 m mudstone, dark grayish purple, massive

**sharp contact**

1.5 m mudstone, light gray and light purplish gray mottled, flinty

**gradational contact**

1.0 m mudstone, dark grayish purple, massive

**gradational contact**

> 1.0 m mudstone, light gray, massive, base of section
Wild Coyote Mesa, Petrified Forest NP
719942

 Channel and point bars

 Flattops sandstone

 Distal overbank paleosol

 Crevasse splay

 Distal overbank paleosol

 Crevasse splay

 Proximal overbank paleosols

 m
630941
Onyx Bridge, Black Forest bed section
23.5 m

0.5 m mudstone, grayish red, carbonate nodules 0.2-2 cm, massive, slickensides
gradational contact

4.6 m mudstone, greyish red with light gray gley spots, massive, slickensides
sharp contact

0.8 m sandstone, fine-medium, light grayish red, mudchip conglomerate
interbeds, tuffaceous, top of Black Forest bed
gradational contact

1.0 m silty mudstone, light grayish red with light gray gley spots
gradational contact

1.9 m siltstone, light grayish red with light gray gley spots, massive
sharp, erosional contact

1.5 m sandstone, fine, light grayish red, thin bedded, ripple cross lamination,
fines upward to silty sandstone, tuffaceous
sharp, erosional contact

2.0 m sandstone, fine-medium, light gray with purplish gray interbeds, large
scale trough cross beds, lateral accretion surfaces, mudchip
conglomerate interbeds, tuffaceous
sharp contact

0.3 m conglomerate, brownish gray weathers to dark brown, carbonate nodule
clasts 2-5 cm
sharp contact

1.7 m sandstone, fine-medium, carbonate cement, small and medium scale
trough cross beds, carbonate nodule and granule conglomerate
stringers, tuffaceous
sharp contact

1.7 m conglomerate, purplish brown, mudstone and carbonate nodule clasts,
granule to 6 cm, 75% mudstone, 25% carbonate nodule, thins laterally
to 0.2-0.5 m
sharp contact

1.7 m interbedded sandstone and mudstone, sandstone: fine, light gray,
parallel and inclined lamination, tuffaceous; mudstone: purple and
gray mottled
gradational contact
1.5 m sandstone, fine-medium, light gray with grayish purple laminations, abundant biotite, parallel to inclined lamination, tuffaceous, large petrified logs (Black Forest) including Onyx Bridge
gradational, interfingering

0-2.0 m conglomerate, light gray to tannish brown, carbonate nodule and mudstone clasts, large scale trough cross beds, clast imbrication in thicker portions, massive where thin, fine tuffaceous sandstone interbeds 0.4 m thick, base of Black Forest bed
sharp, erosional contact

2.3 m mudstone, dark brownish red, top 0.35 m light gray gley and purplish red, carbonate nodules 0.2-2 cm at base, 3-8 cm near top, Scoyenia, massive, mukkara, base of section
Onyx Bridge, Black Forest bed

630941

- overbank paleosol
- distal splay
- proximal overbank
- levee
- channel and point bars

Black Forest bed

- avulsion channel
- avulsion channel
- distal overbank vertisol
2.0 m mudstone, light grayish red with light gray mottles, massive
gradational contact
2.1 m mudstone, reddish brown with light gray mottles, massive
gradational contact
1.0 m interbedded mudstone and silty sandstone, reddish brown to reddish
gray with light gray root halos, fine, top of Black Forest bed
gradational contact
4.2 m sandstone, fine-medium, light gray with grayish purple interbeds,
micaceous, large scale trough cross beds, fines up to silty sandstone,
tuffaceous
sharp contact
0-0.2 m conglomerate, mudchip and carbonate nodule clasts, medium
sandstone matrix
sharp, erosional contact
2.3 m mudstone, dark purplish gray, carbonate concretions 15 cm, massive
gradational contact
2.4 m mudstone, light gray, laminated, grades up to olive gray mudstone
gradational contact
1.5 m sandstone, fine, light purplish gray, large silicified logs (Black Forest),
tuffaceous
sharp contact
3.0-5.0 m conglomerate, carbonate nodule, tuffaceous sandstone interbeds,
poorly preserved carbonized leaf and stem material, permineralized
wood, bones, medium scale trough cross beds, base of Black Forest bed
sharp, erosional contact
2.5 m mudstone, light purple, laminated, carbonate nodules 2-5 cm,
discontinuous carbonate layers 5cm at top, top 0.2 m is gray gley, base
of section
Caveman Cave, Black Forest bed
630942

- distal overbank paleosols
- levee
- channel and point bars
- abandoned channel
- avulsion channel
- distal overbank vertisol

Black Forest bed

m

20
15
10
5
0
727933
Fort Wingate, USGS fossil plant locality 10061
54 m

2.0 m mudstone, brownish yellow and dark reddish brown mottled, massive, slickensides
**gradational contact**
1.1 m mudstone, medium red, carbonate nodules 10cm
**sharp contact**
2.4 m muddy siltstone, dark red, rootlets, massive
**gradational contact**
3.4 m interbedded siltstone and silty sandstone, very fine, light gray to moderate red, laminated and ripple cross laminated
**gradational contact**
1.0 m sandy siltstone, fine, moderate red to yellowish gray, mottled along laminations
**gradational contact**
5.0 m silty sandstone, interbedded light greenish gray and moderate red, parallel and ripple cross lamination, carbonate nodules 10cm at 1.5-2.5 m above base, rootlets
**gradational contact**
8.8 m calcareous mudstone, grey to greenish gray, massive at base, grades up to laminated at top, *in situ* stumps 2, 4.5, 6.5m from base, abundant carbonized macroplants 1.5 m from top (USGS fossil plant locality 10061), silt-sized muscovite abundant near top
**sharp contact**
0.15 m calcareous mudstone, weak red, massive, slickensides
**sharp contact**
1.3 m silty mudstone and muddy siltstone, light greenish gray to light gray, shaley to laminated, parallel and ripple cross lamination, carbonate nodule horizon at base, simple horizontal and vertical burrows
**sharp contact**
1.8 m silty calcareous mudstone, moderate red with light greenish gray mottles, massive, abundant *Scoyenia*, slickensides, grades up to moderate red mudstone, massive, hackly fracture
**sharp contact**
0.55 m muddy calcareous siltstone, moderate to dark red, massive, rootworked, grades up to sandy siltstone
**sharp contact**
1.1 m silty calcareous mudstone, reddish brown, massive
gradational contact
0.12 m muddy silty sandstone, light greenish gray and pale red purple mottled, carbonate nodules 3-5 cm, massive
sharp contact
1.0 m silty mudstone, reddish brown, massive, grades up to mudstone, carbonate nodules 0.5 cm
sharp contact
0.4 m silty sandstone, very fine, greenish gray, parallel and ripple cross lamination
sharp contact
0.9 m silty mudstone, reddish brown, carbonate nodules 0.4-0.6 cm, grades up to mudstone
gradational contact
0.6 m silty calcareous mudstone, grayish blue and grayish red mottled, rootlets, carbonate nodules 0.2-0.6 cm, massive
sharp contact
4.2 m silty mudstone, dark red and light gray mottled, carbonate nodules 4 cm, Scyenia, massive
sharp contact
0.0-0.6 m silty sandstone, very fine-fine, light greenish gray and dark red to yellowish gray mottled, parallel and ripple cross lamination, rootlets with halos, channel fill ~ 50 m wide, trending 345°
sharp contact
0.8 m silty mudstone, moderate red and olive yellow mottled, rootlets with halos, massive
sharp contact
2.3 m mudstone, light gray to pale red purple, slightly calcareous, Scyenia, carbonate nodules 2-3 cm (samples 727933B) increase in size upward, more mottled at top, slickensides, massive
gradational contact
2.3 m mudstone, pale red purple and pale greenish yellow spotted, Scyenia, massive
sharp contact
0.6 m calcareous siltstone, greenish gray and graysih red purple mottled, rottworked, massive, slickensides
sharp contact
4.0 m mudstone, grey , pale red purple and light greenish gray mottled, carbonate nodules 3-6 cm (samples 727933A)
gradational contact
1.0 m mudstone, gray and olive yellow mottled, massive
sharp contact
2.0 m mudstone, moderate red and gray mottled, massive
gradational contact
5.3 m mudstone, gray, gypsum nodules 5-15 cm and veins 0.5 m from base,
base of Monitor Butte Member
sharp, erosional contact
2.0 m calcareous siltstone, moderate red and bluishgray mottled, Fe nodules,
carbonate nodules, calcite veins, blocky fracture, top of Mottled strata,
base of section
Fort Wingate, NM
727933

- overbank paleosols
- Petrified Forest Member
- levee and overbank paleosols
- Monitor Butte Member
proximal overbank wetland

Monitor Butte Member

splay

overbank paleosols

splay

overbank paleosol
Monitor Butte Member

Overbank paleosols

Channel

Overbank paleosols

Lacustrine, abandoned channel, and paleosols

Unconformity paleosol

Mottled strata

Milestone vs. cee cong
Blue Notch Canyon, near White Canyon, UT
30 m

9.0 m sandstone, fine, gray to light brown, thinly bedded, contorted in some places, small to medium scale trough and planar cross beds, coarsens upward to medium-coarse
sharp, erosional contact

9.0 m mudstone, medium to light gray, massive, base of Monitor Butter Member
sharp contact

3.5 m mudstone, very light gray, flinty, hard, massive, abundant vertical, backfilled burrows, top of Shinarump Member
sharp contact

1.5 m mudstone, light gray, massive, Fe replaced roots, Fe nodules
gradational contact

1.0 m silty sandstone, fine, coalified plant material (roots)
sharp contact

0.35 m Fe/Mn nodule, gypsum layer
sharp contact

0.5 m mudstone, medium tp dark gray, massive
gradational contact

2.5 m mudstone, light to medium gray, massive, rootworked, plant material (Equisites), charcoal clasts 2-10 cm, comminuted plant material
gradational contact

0.7 m mudstone, medium gray, massive, slickensides, carbonized roots, logs, base of Shinarump Member
sharp contact

>2 m interbedded siltstone and sandstone, dark brownish red to yellowish brown, Moenkopi Formation, base of section
Blue Notch Canyon 79942

- lacustrine delta
- Monitor Butte Member
- gleysol
- Shinarump Member
- clastic swamp
- sandflat/mudflat
- Moenkopi Formation
Blue Notch Canyon, near White Canyon, UT

18.0 m sandstone, fine, gray to light brown, thinly bedded, contorted in some places, small to medium scale trough and planar cross beds, coarsens upward to medium-coarse, basal carbonate nodule conglomerate, coarsening upward cycles, fine silty sandstone 1.5-3 m near top

sharp, erosional contact

9.0 m mudstone, medium to light gray, grades up to reddish brown, carbonate nodules 2-10 cm, base of Monitor Butte Member

sharp contact

1.7 m mudstone, very light gray, flinty, hard, massive, abundant vertical burrows, top of Shinarump Member

sharp contact

2.7 m mudstone, light gray, massive, abundant Fe concretions, abundant carbonized logs

gradational contact

0.7 m paper coal, grades up to carbonaceous mudstone

sharp contact

0.2 m gypsiferous mudstone

sharp contact

0.1 m coal

sharp contact

0.4 m carbonaceous mudstone, light gray to brownish gray, abundant coalified plants (Equisitites), Fe nodules 2-8 cm, siderite-replaced plant material

sharp contact

0-1.5 m sandstone, medium-coarse, yellowish brown, massive, base of Shinarump Member

sharp contact

>2 m interbedded siltstone and sandstone, dark brown to yellowish brown, Moenkopi Formation
Blue Notch Canyon 79943

Blue Notch Canyon 79943

lacustrine delta

Monitor Butte Member

gleysol

Shinarump Member

clastic swamp

peat swamp

channel

sandflat/mudflat

Moenkopi Formation
Blue Notch Canyon, near White Canyon, UT
33 m

8.5 m sandstone, fine, gray to light brown, thinly bedded, contorted in some places, small to medium scale trough and planar cross beds, coarsens upward to medium-coarse

sharp contact

6.3 m mudstone, light to medium gray, massive, abundant comminuted plant material, base of Monitor Butte Member

sharp contact

2.0 m mudstone, light gray, flinty, massive, abundant burrows, carbonized logs at base, grades laterally into massive gray mudstone, soft, top of Shinarump Member

sharp contact

3. 0 m mudstone, gray, massive

sharp contact

5. 0 m sandy mudstone, light gray, thinly bedded to laminated, cross laminated, abundant plant material (Equisitites), large carbonized trunks, roots

sharp contact

3.7 m mudstone, medium to light gray, abundant plant material (Equisitites), fragments, disrupted lamination, roots

sharp contact

2.0 m mudstone, brownish red with light gray mottles, massive

sharp contact

2.5 m mudstone, light to medium gray, massive, flakey fracture

sharp contact

0.3 m silty sandstone, very fine, light brownish tan, massive, base of Shinarump Member

sharp contact

> 2 m interbedded siltstone and sandstone, dark brownish red to yellowish red, Moenkopi Formation, base of section
Blue Notch Canyon 79944

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lacustrine delta</td>
<td>34.3</td>
</tr>
<tr>
<td>Monitor Butte Member</td>
<td></td>
</tr>
<tr>
<td>gleysol</td>
<td></td>
</tr>
<tr>
<td>stacked clastic swamps</td>
<td></td>
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<tr>
<td>paleosol</td>
<td></td>
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<tr>
<td>sandflat/mudflat</td>
<td></td>
</tr>
<tr>
<td>Moenkopi Formation</td>
<td></td>
</tr>
</tbody>
</table>
9.5 m sandstone, fine-medium, quartz cemented, brownish gray, large scale trough cross beds, primary current lineation, rippled bedding planes, very large scale lateral accretion surfaces, top of Moss Back Member

gradational contact

1.8 m interbedded sandstone and conglomerate, fine-medium, dark brownish gray, carbonate nodule clasts, sandstone 0.3-0.4 m thick, conglomerate 0.5-0.6 m thick, small scale trough cross beds, scour and fill

gradational contact

0.4-0.5 m conglomerate, dark brownish red, carbonate nodule (90%) and reworked sandstone clasts, fine-medium sandstone matrix, large carbonized logs 0.2-0.3 diam, partially replaced by calcite, clast supported at base, matrix supported at top, base of Moss Back Member

sharp, erosional contact

0-0.4 m carbonate nodule layer, coalesced, light brownish gray, 2-20 cm, top of Monitor Butte Member

gradational contact

0.4 m mudstone, brownish red with light gray gley spots and splotches, massive, carbonate nodules 0.5-2 cm

gradational contact

0.5 m carbonate nodule layer, coalesced (>90%), light gray massive mudstone between nodules

gradational contact

1.8 m mudstone, dark grayish purple and purple mottled, abundant carbonate nodules 2-40 cm, larger are coalesced, massive, slickensides

gradational contact

9.0 m mudstone, dark reddish purple, massive, carbonate nodules 2-8 cm

gradational contact

1.5 m silty mudstone, light gray, massive

gradational contact

4.5 m sandstone, fine, light gray, cross lamination, tuffaceous

gradational contact

4.5 m sandstone, fine, light gray, small to medium scale trough cross beds, ripple cross lamination, large silicified trunks at base, tuffaceous, samples 789411, 789412

sharp contact
18.0 m sandstone, fine-medium, light gray, micaceous, medium to large scale trough cross beds, light gray silty sandtone interbeds, poorly preserved plant material
**sharp contact**

14.5 m sandstone, fine-medium, light brown to reddish brown, thinly bedded to laminated, highly deformed, ripple cross lamination and small scale trough cross beds, coarsens up to medium sandstone
**sharp contact, slumped**

2.3 m mudstone, light gray, smectitic, abundant comminuted plant material, fragments, base of Monitor Butte Member
**sharp contact**

1.0 m sandstone, medium-coarse, quartz cement, small scale trough cross beds, equivalent to Shinarump Member
**sharp, erosional contact**

2.7 m mudstone, light gray and dark purplish gray mottled, massive, flaky fracture, Fe nodules 0.2-1.0 cm, top of mottled strata
**gradational contact**

2.8 m mudstone, light brownish yellow mottled, Fe nodules 2-5 cm
**gradational contact**

1.0 m interbedded silty mudstone and silty sandstone, very fine, reddish brown, patchy, massive
**gradational contact**

3.0 m interbedded mudstone and silty mudstone, dark purplish gray to reddish purple with light gray mottles, Fe concretions
**gradational contact**

2.8 m silty sandstone, fine, light gray to brownish yellow with light grayish purple mottles, thinly bedded, small scale trough cross beds, base of mottled strata
**sharp contact**

>1.0 m siltstone, brownish red with light gray mottles, thinly bedded, Moenkopi Formation, base of section
714941
North Six Shooter Peak, UT
47 m

>2.0 m calcareous siltstone, light orangish brown, bioturbated
  gradational contact
3.6 m marly limestone, nodular to massive, bioturbated, crayfish burrows,
  partially silicified
  gradational contact
3.7 m calcareous mudstone, light brownish red, massive, base of Owl Rock
  Member
  sharp contact
0.5 m marly limestone, nodular to massive, discontinuous, bioturbated, top of
  Petrified Forest Member
  sharp contact
4.0 m mudstone, light purplish red, rootlets, massive
  sharp contact
0.5 m nodular limestone, massive
  sharp contact
2.7 m mudstone, brownish red, carbonate nodules 2-4 cm
  gradational contact
4.0 m silty mudstone, light purplish gray, carbonate nodules 2-6 cm, base of
  Petrified Forest Member
  sharp contact
3.9 m sandstone, very fine-fine, light gray to light purplish gray, grades up to
  grayish purple, small to medium scale trough cross beds, tuffaceous,
  top of Moss Back Member, tuff samples 714941
  sharp contact
16.9 m sandstone, fine-medium, grayish brown to light brown, interbedded
  mudchip conglomerate, basal conglomerate, mudstone, carbonate,
  reworked sandstone clasts, woody fragments and trunks replaced by
  calcite, chert, large to very large scale trough cross beds, sets up to 1.5
  m, overturned cross beds, scour and fill, abundant woody fragments on
  bedding planes, base of Moss Back Member
  sharp, erosional contact
>5.0 m interbedded siltstone and sandstone, dark brown to yellowish brown,
  Moenkopi Formation, base of section
710942
Copper Point Camp, White Canyon, UT
8.4 m

0.35 m coal, samples
  **sharp contact**
0.45 m carbonaceous mudstone, black, abundant plant material, samples
  **sharp contact**
0.4 m paper coal, black, samples
  **sharp contact**
0.4 m carbonaceous mudstone, dark gray, abundant plant material, samples
  **sharp contact**
1.8 m interbedded carbonaceous mudstone and sandstone, fine, medium to dark gray with dark orangish brown, base of Shinarump Member
  **sharp contact**
>5.0 m interbedded siltstone and sandstone, dark brown to yellowish brown, Moenkopi Formation, base of section
0.7 m nodular limestone, light reddish gray to light gray, base of Owl Rock Member

gradational contact

7.0 m mudstone, light pinkish orange to orange gray, massive, top of Petrified Forest Member

sharp contact

0-0.3 m sandstone, coarse, carbonate nodule and granule clasts

sharp contact

5.5 m mudstone, gray to light purplish gray, large carbonate concretions, calcite-replaced wood, grades up to light pinkish orange

sharp contact

0.7 m paper coal, samples*

gradational contact

0.8 m carbonaceous mudstone, black to dark gray, abundant plant material, samples*

sharp contact

0.1-0.2 m carbonate nodule horizon, permineralized plant material, teeth, conostrachans, samples*

sharp contact

3.7 m mudstone, light gray, massive, smectitic

sharp contact

1.5-2.0 m sandstone, fine-medium, mudchip conglomerate interbeds, light tannish gray, medium bedded, small to medium scale trough cross beds

sharp contact

15.0 m mudstone, light reddish gray, grades up to laminated muddy siltstone, light gray

gradational contact

3.0 m mudstone, grayish red, massive, carbonate nodules 2-5 cm, base of Petrified Forest Member

sharp contact

>2.0 m sandstone, fine-medium, some coarse grains, contorted, soft-sediment deformation, small to medium scale trough and planar cross beds, top of Monitor Butte Member

* - abandoned channel fill, laterally equivalent to: silty mudstone, light gray, smectitic, sparse comminuted plant material
14.5 m sandstone, fine-medium, reddish brown to yellowish gray, ripple cross lamination, mudchips, Hite bed, top of Church Rock Member and Chinle Formation  
**sharp, erosional contact**

23.0 m sandstone, very fine-fine, brownish red with light gray spots, parallel and ripple cross lamination  
**sharp contact**

12.5 m sandstone, very fine, brownish red with light gray spots, ripple cross lamination, base of Church Rock Member  
**sharp contact**

0.4 m calcareous sandstone, fine, brownish red, bioturbated, top of Owl Rock Member  
**sharp contact**

4.0 m calcareous mudstone, brownish red, massive  
**sharp contact**

1.7 m calcareous sandstone, fine, massive, grades up to calcareous silty sandstone, light purplish red to purplish brown  
**sharp contact**

6.0 m calcareous siltstone, reddish brown  
**sharp contact**

0.4 m nodular limestone, partly silicified, massive  
**sharp contact**

1.9 m calcareous siltstone, light brown to reddish brown  
**gradational contact**

3.0 m calcareous sandstone, very fine, light gray to light grayish red, vertical and horizontal burrows  
**gradational contact**

4.5 m calcareous siltstone, brownish red  
**sharp contact**

0.4 m conglomerate, carbonate nodule/ granule clasts 1-7 cm, light gray to reddish gray  
**sharp contact**

12.0 m calcareous silty mudstone, reddish brown, grades up to calcareous siltstone  
**gradational contact**

0.1 m conglomerate, coarse sandstone matrix, brownish gray to light gray, carbonate nodule clasts 1-5 cm, fines upward to coarse granule sandstone, small scale trough and crude cross beds  
**sharp contact**
0.4 m  marly limestone, massive, bioturbated, pale red to brownish red, gley spots 1-2 mm, rootlets, vertical burrows
  sharp contact
1.3 m  calcareous silty mudstone, brownish red, grades up to calcareous mudstone, reddish brown
  gradational contact
0.8 m  limestone, light gray to reddish brown, laminated, partly silicified
  gradational contact
0.5 m  marly limestone, light grayish red to light gray, nodular to crudely bedded
  gradational contact
1.7 m  calcareous silty mudstone, grayish red to brownish red
  gradational contact
0.8 m  calcareous sandstone, very fine, light gray to reddish gray, small scale trough and ripple cross lamination, calcareous siltstone interbeds, light gray to light reddish brown
  gradational contact
1.7 m  calcareous silty sandstone, very fine, light brownish red with light gray mottles, ripple cross lamination, calcareous mudstone mudstone interbeds, light brownish red
  gradational contact
3.5 m  calcareous mudstone, brownish red, carbonate nodules 2-5 cm
  gradational contact
1.8 m  sandstone, medium-coarse, with conglomerate interbeds, small scale trough cross beds, carbonate nodule clasts 2-5 cm, unionid bivalves
  gradational contact
0.5 m  conglomerate, carbonate nodule clasts 2-5 cm, unionid bivalves
  sharp contact
1.0 m  calcareous sandstone, very fine, ripple cross and parallel lamination, shallow horizontal burrows
  sharp contact
1.1 m  silty sandstone, very fine, reddish brown, ripple cross and parallel lamination, grades up to calcareous sandstone
  gradational contact
2.2 m  calcareous sandstone, very fine-fine, red to light reddish brown, thinly bedded, ripple cross on parallel lamination
  sharp contact
0.4 m  calcareous silty sandstone, fine, light brownish red, grades up to calcareous siltstone
  gradational contact
0.5 m  calcareous sandstone, very fine, reddish brown with light gray mottles, ripple cross lamination, bioturbated
  sharp, erosional contact
3.2 m calcareous silty mudstone, reddish brown
  gradational contact
1.0 m calcareous siltstone, reddish brown, carbonate nodules 2-5 cm
  gradational contact
4.5 m calcareous mudstone, reddish brown, carbonate nodules 2-3 cm
  gradational contact
6.0 m calcareous siltstone, reddish brown, wavy lamination
  gradational contact
6.0 m calcareous mudstone, reddish brown
  gradational contact
1.0 m calcareous siltstone, reddish brown
  gradational contact
2.5 m calcareous silty mudstone, brownish red
  gradational contact
2.7 m calcareous silty sandstone, fine, calcareous siltstone interbeds, reddish brown, small scale trough and ripple cross lamination, fines upward to calcareous siltstone
  sharp contact
0.6 m calcareous sandstone, very fine, light gray, ripple and parallel lamination, fines upward to calcareous mudstone, reddish brown
  sharp contact
2.8 m calcareous sandstone, very fine, coarse-granule interbeds, reddish gray with light gray spots, small scale trough and ripple cross lamination, grades up to interbedded calcareous mudstone and silty sandstone, light gray to reddish gray, and then to reddish gray to reddish purple calcareous mudstone
  sharp contact
0.3 m conglomeratic sandstone, fine-coarse, fines upward, carbonate nodule clasts 2-5 cm
  sharp contact
1.0 m calcareous mudstone with nodular limestone, light greenish gray to brownish red, grades up to nodular limestone
  gradational contact
22.5 m calcareous mudstone, brownish red
  gradational contact
1.5 m muddy siltstone, light gray, laminated
  sharp contact
2.6 m calcareous mudstone, light brownish red
  sharp contact
0.25 m conglomerate, light gray and light red mottled mudstone and carbonate nodule clasts 0.5-1 cm, grades laterally into fine sandstone
  sharp contact
5.5 m calcareous mudstone, brownish red, grades up to brownish red with light gray mottles

gradational contact

0.7 m calcareous mudstone, brownish red and light gray mottled, carbonate nodules 2-5 cm

gradational contact

3.6 m calcareous mudstone, reddish brown to orange brown with light gray mottles, grades up to brownish red

sharp contact

0.6 m calcareous silty sandstone, coarse transported carbonate clasts, light reddish brown to orange brown

sharp contact

2.2 m calcareous silty mudstone, light reddish brown to orange brown, carbonate nodules 5-10 cm

sharp contact

0.6 m limestone, brownish red and brownish gray, rootlets, crayfish burrows

sharp contact

4.0 m calcareous mudstone, light brownish red to orange red, massive

sharp contact

0.7-1.0 m limestone, brownish red and brownish gray mottled

sharp contact

9.3 m interbedded nodular marly limestone and calcareous mudstone, light orangish gray to tan and light brown to light reddish brown, limestone 0.1-0.3 m, mudstone 0.5-1.0 m

sharp contact

0.5 m limestone, brownish red and brownish gray mottled, disrupted but with some bedding, partially silicified, locally nodular

sharp contact

14.5 m calcareous mudstone, brownish red to orangish red with light greenish gray mottles, carbonate nodules 1-2 cm in basal 3 m

gradational contact

0.3 m mudstone, purplish gray, with large irregular, cylindrical carbonate nodules up to 30 cm, partially replaced by silica, base of Owl Rock Member

sharp contact

13.5 m mudstone, light brownish red and light gray mottled, light greenish gray gley spots, carbonate nodules 0.2-2 cm, top of Petrified Forest Member

sharp contact

1.3 m mudstone, dark brownish red, massive, slickensides, upper tuff unit (tuff sample 711941b)

sharp contact
0.4-0.5 m silty sandstone, light gray to orangish tan, micaceous, lower tuff unit
(tuff sample 711941a)
gradational contact
2.7 m silty mudstone, brownish red, with tuffaceous sandstone interbeds,
light greenish gray, carbonate nodules 0.2-2 cm
gradational contact
1.0-1.5 m interbedded sandstone and muddy sandstone, fine, light gray with
grayish purple interbeds
gradational contact
6.0 m sandstone, fine-medium, light gray, small and medium scale trough
cross beds
sharp contact
5.5 m interbedded sandstone and conglomerate, fine, carbonate nodule and
sandstone clasts 5-12 cm, brown and reddish brown to light gray and
light brownish gray, conglomerate 0.4-0.5 m, sandstone 0.5-1.2 m, basal
carbonate nodule conglomerate, large silicified trunks
sharp, erosional contact
5.0 m mudstone, reddish purple to reddish brown, large carbonate nodules 5-
30 cm, grades up to grayish purple
sharp contact
4.0 m mudstone, purplish gray, smectitic, massive, slickensides, Scoyenia
gradational contact
3.0 m interbedded silty sandstone and siltstone, fine, tuffaceous, small and
medium scale trough cross beds, sandstone 0.2-0.3 m, siltstone 0.3-0.4 m, smectitic, fines upward
sharp contact
1.5 m mudstone, light gray, smectitic, carbonate nodules 2-5 cm, massive
sharp contact
5.0 m mudstone, light gray, smectitic, carbonate nodules 5-15 cm, massive,
slickensides, grades up to purplish gray
sharp contact
1.5 m mudstone, dark reddish brown, smectitic, massive, slickensides
gradational contact
6.0 m silty mudstone, grayish purple and light gray mottled, smectitic,
massive with some disrupted lamination, slickensides
gradational contact
2.0 m silty mudstone, light gray and purplish gray mottled, smectitic, massive
gradational contact
7.0 m muddy siltstone, light gray, smectitic, massive
gradational contact
1.0 m mudstone, light purplish gray and light gray mottled, massive, base of
Petrified Forest Member
gradational contact
9.0 m mudstone, brownish red, carbonate nodules 1-10 cm, massive, base is light purplish gray, Monitor Butte equivalent
gradational contact
2.5 m interbedded sandy siltstone and siltstone, light grayish red with light gray and dark reddish brown mottles, massive, Fe concretions, crayfish burrows, "Mottled strata"
gradational contact
1.8 m sandstone, fine, tan with purplish gray mottles, large and medium scale trough cross beds, altered Moenkopi, "Mottled strata", base of Chinle Formation
sharp contact
>1 m siltstone with sandstone interbeds, fine-medium, dark brown and yellowish gray, top of Moenkopi Formation, base of section
Appendix E: Tables of Sedimentologic and Taphonomic Data
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### Crevasse Splay

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