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# REVISED STRATIGRAPHY OF THE LOWER CHINLE FORMATION (UPPER TRIASSIC) OF PETRIFIED FOREST NATIONAL PARK, ARIZONA

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**ABSTRACT**— The Sonsela Sandstone bed in Petrified Forest National Park is here revised with specific lithologic criteria. It is raised in rank to Member status because of distinct lithologies that differ from other members of the Chinle Formation and regional distribution. Informal stratigraphic nomenclature of a tripartite subdivision of the Sonsela Member is proposed that closely mimics past accepted nomenclature to preserve utility of terms and usage. The lowermost subdivision is the Rainbow Forest beds, which comprise a sequence of closely spaced, laterally continuous, multistoried sandstone and conglomerate lenses and minor mudstone lenses. The Jim Camp Wash beds overlie the Rainbow Forest beds with a gradational and locally intertonguing contact. The Jim Camp Wash beds are recognized by their roughly equal percentages of sandstone and mudstone, variable mudstone features, and abundance of small (<3 m) and large (>3 m) ribbon and thin (<2 m) sheet sandstone bodies. The Jim Camp Wash beds grade into the overlying Flattops One bed composed of multistoried sandstone and conglomerate lenses forming a broad, sheet-like body with prevalent internal scours. The term “lower” Petrified Forest Member is abandoned in the vicinity of PEFO in favor of the term Blue Mesa Member to reflect the distinct lithologies found below the Sonsela Member in a north-south outcrop belt from westernmost New Mexico and northeastern Arizona to just north of the Arizona-Utah border. The Petrified Forest Member is here restricted in the vicinity of PEFO to the red mudstone-dominated sequence found between the Sonsela Member and the Owl Rock Member.

**Keywords: Triassic, Petrified Forest, Chinle Formation, stratigraphy, Sonsela, Blue Mesa**

## INTRODUCTION

PETRIFIED FOREST National Park (PEFO) is a focal point for studies of Upper Triassic terrestrial strata in the American Southwest. Despite numerous studies of plant and vertebrate remains, stratigraphic assessment of the Chinle Formation has lagged behind. Previous biostratigraphic study has indicated a change in the fauna and flora in the middle of the PEFO section, surrounding the level of the Sonsela Sandstone (Long and Padian, 1986; Litwin et al., 1991; Lucas and Hunt, 1993; Long and Murry, 1995; Murry and Kirby, 2002). However, detailed lithostratigraphic studies have not concentrated on this important interval, despite their importance for any biostratigraphic framework.

Lithostratigraphic study of the PEFO region, south of the Navajo and Hopi Reservations, began in earnest with Cooley (1957; 1958; 1959) and Akers et al. (1958). Stewart et al. (1972a) produced an overview of the regional lithostratigraphy, but did not focus on the PEFO section. Billingsley et al. (1985) produced the first full geologic map of PEFO at a 1:50,000 scale and Billingsley (1985) published a companion explanation of PEFO stratigraphy. Billingsley’s (1985) and Billingsley et al.’s (1985) work largely followed the nomenclature of previous workers, and was the standard for the stratigraphy of PEFO that was followed by most workers for the next 15-20 years with only local additions and revision (Ash, 1987; Ash, 1992; Therrien and Fastovsky, 2000; Hasiotis et al., 2001).

During the 1990s views regarding the stratigraphy of the Chinle Formation, and thus PEFO, split into two main philosophies. One philosophy continued along the lines of Stewart et al. (1972b) and Billingsley, Breed, and Ash (Billingsley, 1985; Billingsley et al., 1985) maintaining informal regional lithologic unit designations, and emphasizing regional correlations between units (e.g., Dubiel, 1994; Lehman, 1994; Dubiel et al., 1999). The other philosophy was initiated by Lucas and colleagues (e.g., Lucas and Hayden, 1989; Lucas and Hunt, 1989; Lucas, 1991; Lucas, 1993; Lucas et al., 1997; Lucas et al., 1999) who incorporated all Upper Triassic terrestrial strata of western North America into the Chinle Group and either formalized existing local nomenclature into broad members, abandoned existing stratigraphic nomenclature or changed the stratigraphic rank of units.

Recently, Heckert and Lucas (2002b) expanded the Sonsela Member (=Sonsela Sandstone bed) within PEFO by introducing a tripartite subdivision. The new revision is similar to what is observed at the type section of the Sonsela (Akers et al., 1958) and incorporates some observations seen by previous workers that indicated that the Sonsela within PEFO consists of several sandstone beds (Cooley, 1957; Roadifer, 1966). However, the stratigraphy as proposed by Heckert and Lucas (2002b) includes correlations of subunits contradictory to mapping and does not provide a sound foundation for the recognition of units on a regional level. Regional recognition of the Sonsela has been complicated in the past by subjective interpretation of isolated sandstone bodies that may or may not be restricted to the Sonsela interval throughout the region.

The present study was initiated independently of Heckert and Lucas (2002b) and aims to provide a consistent framework for the Sonsela interval on which to base other studies. Lithologic criteria are given to recognize the Sonsela and its three subunits, and justify the status of the Sonsela as a member of the Chinle Formation. The lithostratigraphic framework presented here provides a background for recognition of the Sonsela on a regional level, as well as locally within the PEFO area.

## BACKGROUND

*Geologic setting.*—The Chinle Formation is a collection of fluvial, lacustrine and floodplain rocks that were deposited in a back-arc basin formed inland of a Late Triassic magmatic arc associated with the subduction zone off the west coast of North America (Dickinson, 1981; Dickinson et al., 1983; Fig. 1). Local subsidence was controlled by tectonic events associated either with a dynamic forebulge of the island-arc portion of the magmatic arc (Lawton, 1994) or local uplifts, such as the Mogollon Highlands along the continental portion of the magmatic arc (Harshbarger et al., 1957; Stewart et al., 1972b; Dickinson, 1981) and the ancestral Front Range and Uncompahgre uplifts (Stewart et al., 1972b; Dubiel, 1991; Dubiel, 1994; Lucas et al., 1997). Dubiel (1992) and DeLuca and Eriksson (1989) documented movement on the Ancestral Rockies uplifts near the time of Sonsela deposition. Local salt tectonism during the Late Triassic has been documented by several workers (Blakey and Gubitosa, 1983, 1984; Hazel, 1991; Dubiel, 1994).

The climate during Chinle deposition has been described as humid or subhumid to semiarid. Dubiel et al. (1991, p. 364) interpreted the “lower” Petrified Forest interval as representing an “unusual[ly] wet episode”. Vertebrate faunas are typically dominated by aquatic to amphibious forms such as metopsaurid amphibians and crocodile-like phytosaurs attesting to prevalent lakes and streams, although certain ‘upland’ elements, such as dinosaurs, rauisuchians, dicynodonts and aetosaurs are locally pervasive, particularly in strata above the Sonsela interval (Colbert, 1972; Long and Murry, 1995). Ash has interpreted the flora of PEFO as indicative of a humid environment (1972; 1986; 1992). Gottesfeld (1972) interpreted distinct upland, lowland and riparian floras in an overall arid to semiarid environment with through flowing streams dominating the paleohydrology of the riparian and lowland floras. Demko (1995a; 1995b) arrived at a conclusion similar to Gottesfeld (1972) during a study of the taphonomy of plant localities. Paleosols below and at the base of the Sonsela interval were compared to modern subhumid forest soils by Retallack (1997). Jones (2000) interpreted a shift towards drier climates near the base of the Sonsela. Other studies have indicated a semiarid climate marked by episodes of heavy precipitation (Blodgett, 1988; Dubiel et al., 1991; Dubiel, 1994; Therrien, 1999; Therrien and Fastovsky, 2000).

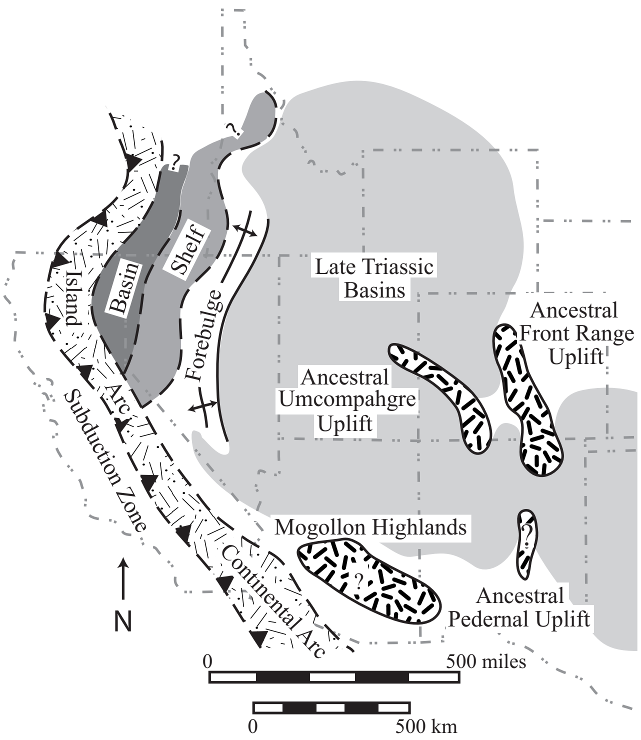

Figure *1*. Geologic setting for the Late Triassic of western North America. The Chinle basin extends from the west side of the ancestral Rocky Mountain uplifts of the ancestral Uncompahgre and Front Range uplifts in Colorado and northern New Mexico to the magmatic arcs and forebulge in Nevada and western Arizona. The western edge of the Dockum basin is shown to the east of the ancestral Front Range and possible Pedernal uplifts. The extent and timing of the ancestral Pedernal Uplift and Mogollon Highlands are debated. Modified from Lawton (1994).

*Stratigraphic nomenclature.*—The name Chinle Formation was first proposed by Gregory (1917) for Upper Triassic terrestrial rocks on the Navajo Reservation of northern Arizona. Gregory subdivided the Chinle into four units, A though D, in descending order (Fig. 2.1). Division A included the upper part of the Chinle that is dominated by red mudstones and siltstones. Division A has been variously assigned to the Ochre, Orange siltstone, Church Rock or Rock Point members depending on location and predominant lithology (Stewart et al., 1972a, 1972b; Lucas et al., 1997). Division B consisted of the laterally persistent limestone bearing part of the Chinle below division A and was subsequently formalized as the Owl Rock Member (Stewart, 1957; Witkind and Thaden, 1963). Division C, the dominantly variegated middle portion, was later formally named the Petrified Forest Member by Gregory in 1950. The Petrified Forest Member was named for the exposures in and around PEFO, but the type section is near Zion National Park (Gregory, 1950). Division D represents the basal portion of the Chinle Formation of Gregory and is characterized by relatively inconsistent lithologies, typically with relatively high sandstone/mudstone ratios, although still mostly mudstone. Division D has been assigned to the siltstone and sandstone member (= Cameron Member of Lucas, 1993), Monitor Butte Mem-

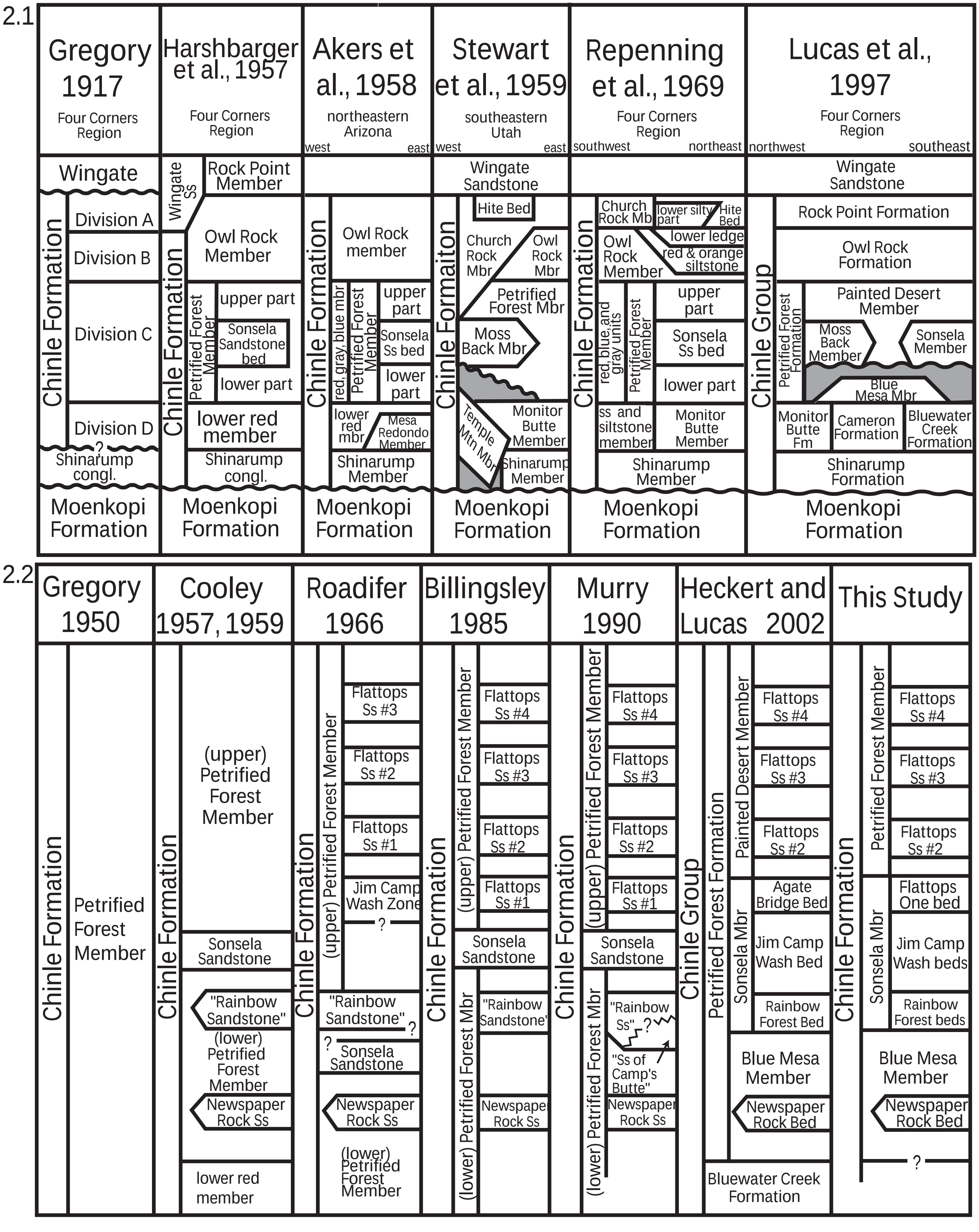

Figure *2*. Stratigraphic correlation chart for the Chinle Formation. *2.1*. Stratigraphic correlation chart for the Four Corners region of Arizona, Colorado, New Mexico, Utah; *2.2*. Stratigraphic correlation chart for the PEFO region. Note the variable relative positions and nomenclature of the units assigned to the Sonsela Member.

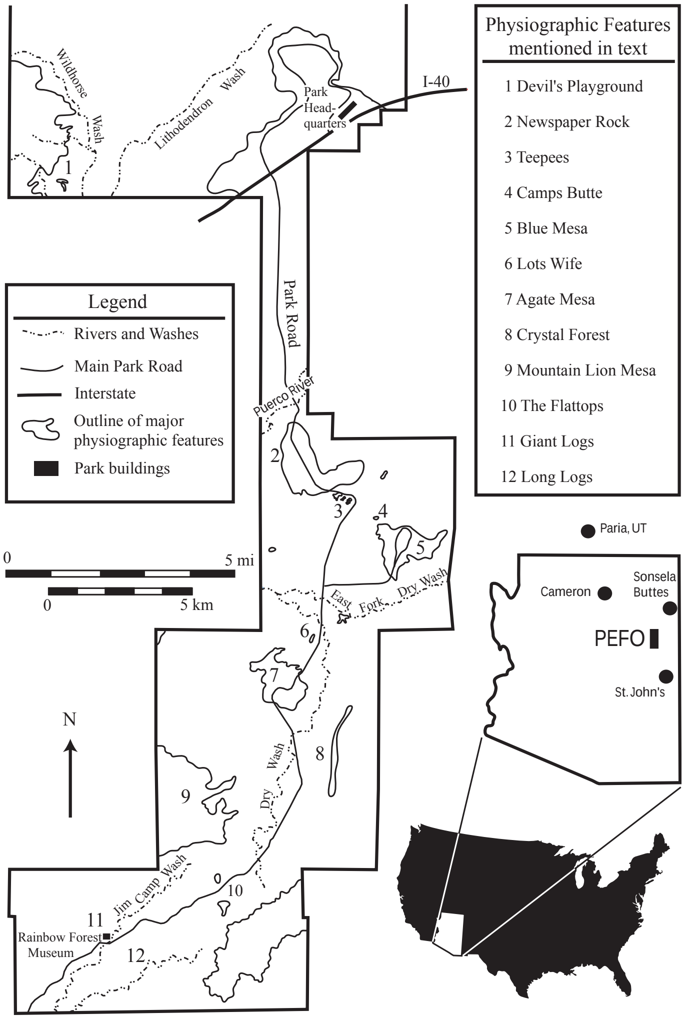

Figure *3*. Study area of the southern portion of PEFO. Major physiographic features discussed in text are listed. Inset shows position of PEFO relative to the type area of Sonsela Buttes, and towns in Arizona and Utah mentioned in text regarding outcrop distributions.

ber, Mesa Redondo Member, or lower red member (=Bluewater Creek Member of Lucas and Hayden, 1989), depending on the dominant facies (Cooley, 1958; Witkind and Thaden, 1963; Stewart et al., 1972a, 1972b; Lucas et al., 1997).

Akers et al. (1958) named a distinctive ledge-forming sandstone unit near the middle of the Petrified Forest Member, the Sonsela Sandstone bed. The type section is 3½ miles from the western-most Sonsela Butte near the Arizona-New Mexico border (Fig. 3). At its type section, the Sonsela consists of a lower sandstone, medial mudstone, and upper sandstone subdivisions. In other areas, the unit was recognized as a single sandstone bed or as an interval of several sandstone lenses (Cooley, 1957, 1959; Repenning et al., 1969). The recognition of the Sonsela led to division of the Petrified Forest Member into informal "lower" and "upper" members based upon both the relative position to the Sonsela interval and the lithologic and color changes that were locally observed (Akers et al., 1958; Repenning et al., 1969).

Various sandstone beds within PEFO have been informally described and associated with the Sonsela Sandstone bed (Fig. 2.2). Cooley (1957) informally named the Rainbow Forest sandstone for the log-bearing sandstone and conglomerate at the Giant Logs and Long Logs "forests" near the southern end of PEFO. He commented on its lithologic similarity to the more widely recognized Sonsela Sandstone bed of PEFO and postulated that the Rainbow Forest sandstone was possibly a lower tongue of the Sonsela. Cooley (1957) commented on the existence of several other unnamed tongues of the Sonsela within PEFO. Roadifer (1966, p. 19) believed that the Rainbow Forest sandstone was located 20 ft (~6 m) stratigraphically above the Sonsela. The Jim Camp Wash zone was named by Roadifer (1966) for an interval of interbedded sandstone and mudstone stratigraphically above the Rainbow Forest sandstone along Jim Camp Wash north of Giant Logs. Roadifer postulated that this interval may also represent an upper tongue of the Sonsela, similar to his assessment of the Rainbow Forest sandstone. In the same report Roadifer also named the Flattops sandstones, numbered 1 to 3, in ascending order, for laterally persistent sandbodies above the Sonsela Sandstone bed within the upper part of the Petrified Forest Member.

Billingsley et al.'s (1985) geologic map and Billingsley's (1985) stratigraphic description of PEFO only recognized the Sonsela Sandstone as a single sandstone bed. Billingsley et al. agreed with Cooley that the Rainbow Forest sandstone was stratigraphically below the Sonsela but did not associate the two. Whereas Billingsley et al. did not recognize the Jim Camp Wash zone of Roadifer (1966), they did recognize the Flattops sandstones. However, Flattops sandstones 1, 2 and 3 of Roadifer became Flattops sandstones 2, 3 and 4, respectively, of Billingsley et al.. Billingsley (1985) reassigned the name Flattops sandstone #1 for laterally persistent sandstone between the Rainbow Forest sandstone and Flattops sandstone #2 that is probably equivalent to Roadifer's Jim Camp Wash zone (see Heckert and Lucas, 2002b). Deacon (1990, pg. 7) agreed with Roadifer that the Rainbow Forest sandstone represents an upper tongue of the Sonsela Sandstone bed and was "part of the same fluvial system". Ash (1987) and Creber and Ash (1990) recognized the Rainbow Forest sandstone as a separate unit below the Sonsela. Murry (1990) described an informal sandstone on Camp Butte northeast of Blue Mesa and interpreted it as a possible lateral equivalent to the Rainbow Forest sandstone. Both Murry (1990) and Demko (1994; 1995a; 1995b) associated the Rainbow Forest sandstone and Sonsela Sandstone bed and cited them as the "Rainbow-Sonsela Complex" without discussion of the stratigraphic relationship between the two sand bodies.

Lucas (1993) raised the Petrified Forest Member to formational rank. He also raised the rank of the Sonsela Sandstone bed to member status, and named the Blue Mesa and

Painted Desert members of the Petrified Forest Formation for what was previously considered the lower and upper portions of the Petrified Forest Member, respectively. Heckert and Lucas (1998b) directly correlated the Rainbow Forest sandstone and the traditional Sonsela Sandstone bed (*sensu* Akers et al., 1958) in their description of the stratigraphic distribution of petrified wood within PEFO. Later, Heckert and Lucas (2002b) proposed a tripartite subdivision of their Sonsela Member, which will be further discussed below.

## METHODS

This study was conducted using standard stratigraphic section measuring techniques. Nineteen sections were measured and correlated in the southern portion of PEFO. Section locations were chosen based on obtaining representative lateral variability, representative facies, and access to a known stratigraphic level for the base and top of the section. Where possible, the entire Sonsela Member was measured, as well as a portion of the underlying and/or overlying strata (i.e., Camp Butte and Blue Mesa 1 sections). Stratigraphic relations were observed along outcrop in various portions of PEFO, including the southern part of the park and the Devil's Playground area (Fig. 3) north of I-40. A preliminary 1:24,000 scale map was produced by standard geologic mapping practices. Representative hand samples and thin sections were collected and examined to enhance lithologic description and to compare to previous studies (e.g., Espegren, 1985; Deacon, 1990).

## DESCRIPTION OF SEDIMENTARY FACIES

The present study recognizes eight sedimentary facies assemblages (A-H) in the medial portion of the Upper Triassic section in PEFO from the measured sections and outcrop descriptions. The term "facies assemblages" is used in a modified form, similar to that of Parsons et al. (2003). Facies assemblages in this study designate lithologies or groups of lithologies that are connected by similarities in characteristic features and architecture between facies associations that are recognizable in outcrop. Characteristic features include relationships between facies associations, sandstone composition, sandstone/mudstone ratios, architectural relationships, and paleosol characteristics. The assemblages form the basis of the stratigraphy described below.

*Facies Assemblage A.*—Facies assemblage A is present at the base of the study section. This assemblage is dominated by dusky-blue, blue-gray and gray claystone and mudstone with locally common purple and local green, yellow, and red mudstone. Most non-gray mudstone has diffuse gray, blue-gray or green-gray mottling. Red and/or purple mottles may be present in gray and blue-gray beds. The traceability of individual mudstone units is variable, although most are only traceable for distances between 50 and 500 m, where topography permits. Contacts between beds are typically gradational. Small rhizoliths preserved as carbonate or silica are locally common. Moderate to large slickensides are common in several horizons, but are not consistently present. Carbonate nodules are common in particular horizons and only locally follow slickenside and/or root traces (Demko, 1995b; Therrien and Fastovsky, 2000). Paleosol profiles are typically composite (cf., Marriott and Wright, 1993) resulting in thick profiles, often thicker than several meters (Fastovsky et al., 2000).

Sandstone is uncommon in facies assemblage A. Where present, sandstone bodies typically have sheet-like geometries with width/thickness ratios (W/T) >50-100. Locally sandstone bodies have W/T ratios of about 15-25 and fill shallow scours. True ribbons (cf., Friend et al., 1979) are rare. Sandstone beds are typically <0.5 m thick, and rarely over 1 to 3 m thick. Sandstone is typically greenish-gray, but can range from light- to pinkish-gray on fresh surfaces. Sandstone is usually texturally and compositionally immature with large percentages of matrix and pseudomatrix from the alteration of volcanic clasts (Roadifer, 1966). Sandstone is typically lithic wackes. Most sandstone is poorly indurated and preserved sedimentary structures are rare.

Facies assemblage A is interpreted here as predominantly floodplain deposits. Pedogenic features indicate moist conditions with some seasonal variation in drainage (Vepraskas, 1994; PiPujol and Buurman, 1997; Retallack, 1997). The predominance of diffuse mottles indicates that groundwater was the predominant means of saturation (Duchaufour, 1982; PiPujol and Buurman, 1994). The predominance of composite paleosol profiles suggests stable landforms (Kraus and Aslan, 1993; Marriott and Wright, 1993; Kraus, 1997), although slight variations in floodbasin-scale base level are interpreted from the lack of lateral continuity of beds and scour surfaces. Sandstone bodies are interpreted as ephemeral tributary or crevasse channels extending out onto the floodplain, or as rare sheetflood deposits.

*Facies Assemblage B.*—Facies assemblage B consists of medium-grained, locally fine- to coarse-grained, sandstone and local conglomerate. The sandstone is typically gray to pinkish-gray or pale tan on fresh surfaces. Sandstone is generally compositionally mature to submature and texturally mature (Woody, 2003). The unit is multi-storied and forms a sheet that can be traced for several kilometers in the vicinity of Blue Mesa. Individual stories are typically 10-60 cm thick. Thickness of the assemblage ranges from 0 m at its pinchout at Lots Wife, to ~16 m at Blue Mesa. Moderate- and large-scale crossbedding (5-15 cm and >15 cm, respectively) is common. The base of the assemblage is generally a shallow scour with local relief typically less than 1 m. The assemblage typically weathers to low ridges due to poor induration, but locally caps small buttes, such as Camp Butte, where it is well-indurated.

Granules of chert or mudstone rip-up clasts commonly define crossbedding. Lag deposits of moderately to very weakly rounded vertebrate remains are locally present. Volcanic and yellow, white, or orange chert pebbles form local lenses within the unit, particularly where the unit is thicker and coarser grained. Quartzite forms a minority of clasts in lenses with volcanic and chert clasts. Sandstone is lithic arenites to lithic wackes. Petrified wood occurs locally as trunk fragments up to 1 m in diameter, but typically less than 30 cm. Fragments longer than 1 m are rare. Most observed *in situ* wood fragments are oblique to perpendicular to paleoflow.

The multi-storied nature, predominance of large-scaled crossbedding and lack of mudstone indicates that facies assemblage B was deposited by a low-sinuosity, bedload stream system (Miall, 1977; Blodgett and Stanley, 1980; Miall, 1985).

*Facies Assemblage C.*—Facies assemblage C is composed of medium-to coarse-grained, locally fine-grained, sandstone. Sandstone is typically light (light gray to pinkish-gray), but locally is maroon or medium gray. Texturally it is typically mature to submature. In the upper part of the assemblage and near the edges of lenses textural maturity can be immature to very immature. The assemblage weathers to irregular ridges and flats where texturally immature and moderately- to poorly-indurated, and forms resistant, low ridges where texturally mature and well-indurated. Large-scale crossbedding is the most abundant sedimentary structure. Lateral accretion sets (cf., Allen, 1965) are locally seen in the upper portion of assemblage C.

Compositional maturity is highly variable but is typically submature (Woody, 2003). Pebble- to cobble-sized gravel clasts comprise 0 to ~70% of the unit, typically concentrated along bedding surfaces or as massive "lag" deposits. Gravel consists of extrabasinal volcanic, quartzite and chert clasts and intrabasinal mudstone rip-ups, rounded vertebrate remains, and rare carbonate nodules. Chert clasts are typically white, yellow, orange, or less commonly brown. Sandstone is lithic wackes to lithic arenites. Petrified wood is typically abundant as brightly colored logs (Ash and Creber, 1992; Heckert and Lucas, 1998b; Ash and Creber, 2000).

Mudstone is typically rare but increases in abundance near the top of the unit. Lenses of mudstone are relatively common at the top of the assemblage where it interfingers with assemblages D and E. Mudstone ranges from dusky-blue to gray. Dusky-blue mudstone typically possesses common large to small gray mottles, although they are locally absent. Other pedogenic features are generally absent, although large-scale slickensides do occur locally. Small, but very abundant carbonate nodules locally accompany the slickensides and are often aligned with the slickenside surfaces. Carbonate rhizocretions and rhizoliths are typically also observed in these areas.

The base of facies assemblage C is not well exposed but appears to be very similar to facies assemblage B. The sheet-like morphology and internal scours between stories is also similar to assemblage B. The main differences are the more abundant gravel and lenses of mudstone and sandstone in the upper portion of assemblage C.

The predominance of gravel clasts, morphology, and prevalence of large-scale crossbedding suggest that facies assemblage C was also deposited by a low-sinuosity stream system (e.g., Jackson, 1978; Brierley, 1996). Increasing sinuosity and/or increased avulsion frequency is indicated by mudstone lenses and lateral accretion sets in the upper portion of the unit (Allen, 1965; Jackson, 1978; Ethridge et al., 1999). The lack of, or small and subdued nature of pedogenic features in most exposures suggest little time for pedogenesis before burial (Marriott and Wright, 1993; Kraus, 1997). The nature of these pedogenic features is consistent with weak groundwater gleying (Duchaufour, 1982; Vepraskas, 1994). Where pedogenic features are more pronounced they suggest a predominance of surface water gley during seasonally poor drainage conditions (PiPujol and Buurman, 1994, 1997; Vepraskas, 1992).

*Facies Assemblage D.*—Facies assemblage D consists of a complex of sandstone sheets and ribbons (cf., Friend et al., 1979), and mudstone. Sandstone/mudstone ratios are generally ~2.5-1. Sandstone is typically fine-grained and poorly sorted. Sandstone is typically a shade of gray or tan on fresh surfaces, but weathers into a wide variety of colors. Sandstone textural and compositional maturity is generally immature, but is locally submature (Woody, 2003). Ribbons vary from <1 m to ~3 m thick, but all have W/T ratios <10. Ribbons at the top of the assemblage can reach ~5 m in thickness. Sheets are usually <0.5 m in thickness and usually traceable throughout the outcrop (up to 1-2 km). In a few locations sheets can be traced to where they connect several ribbon sandstones (Fig. 4.1), similar to the "tiers" of Kraus and Gwinn (1997). Granule- to pebble-sized gravel within ribbons is rare, but where observed it is typically intraformational in nature. In a few locations dark chert (mostly black and brown) and volcanic clasts were observed in lenses of texturally very immature conglomerate to sandy conglomerate. Sandstone is typically lithic wackes. Petrified wood is relatively rare, with most being in sandstone ribbons in the upper part of the facies assemblage.

Mudstone ranges in color from dusky-purple to red to dusky-blue to gray, in decreasing order of abundance. Individual beds typically are less than 1 m and can be traced for ~1 km, before they are lost due to erosional truncation. Bed contacts are often sharp. Most mudstone exhibits gray mottling, particularly prevalent along slickensides and root traces. Slickensides are variable in development but are rarely larger than 0.3 m in height. Carbonate nodules are often present, but rarely in high abundances. A thin (<10 cm), orange to red siliceous horizon is seen in the lower third of the assemblage at several

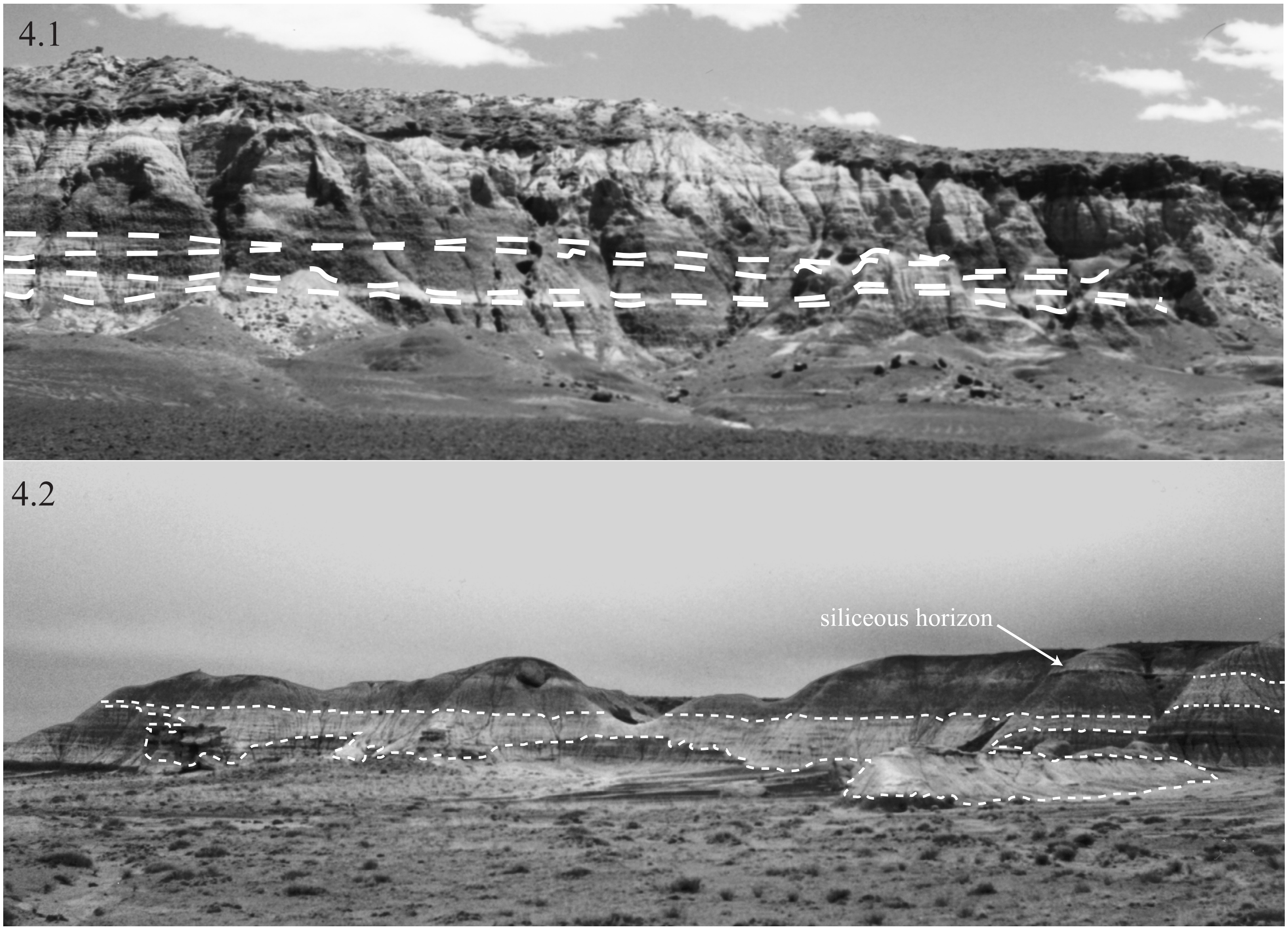

Figure *4*. Sandstone 'tiers' low in facies assemblages D and E (Jim Camp Wash beds). *4.1*. Sandstone "tiers" on the east face of Blue Mesa; *4.2*. Sandstone "tier" connecting three small ribbons immediately below the siliceous horizon near Mountain Lion Mesa. Note the relatively lower W/T and deeper basal scour of the ribbons relative to those in 4.1. The presence of several ribbon sandstone bodies connected with a thin sheet sandstone body is one of the criteria for recognizing avulsion deposits listed in Kraus and Wells (1999). These types of deposits are relatively common throughout facies assemblages D and E (Jim Camp Wash beds).

locations in the Blue Mesa area. This siliceous horizon typically exhibits a coarse dendritic pattern on the upper surface.

Facies assemblage D is interpreted as a floodplain deposit in the outer part of the avulsion belt. The ribbon and sheet sandstones as well as common intervals of thinly interbedded sandstone and mudstone (heterolithic deposits) closely resemble the characteristics cited by Kraus and Wells (1999), among others, as indicative of avulsion processes. The lack of thick ribbon and sheet sandstones suggest a more distal position to the site of avulsion and crevasse-splay deposition. The larger ribbons at the top of the assemblage may indicate environments closer to the trunk channel.

The pedogenic features of the mudstone indicates that they are moderately- to poorly-drained paleosols predominantly affected by surface water gleying (PiPujol and Buurman, 1994; Vepraskas, 1994). The moderately- to poorly-drained paleosols are also suggestive of a relatively medial floodplain deposition. More proximal positions are subjected to the influence of frequent, relatively coarse-grained deposition that would promote better drainage (Bown and Kraus, 1987; Pizzuto, 1987; Marriott, 1996; Kraus, 1997) . The coarse dendritic morphology of the siliceous material suggests preservation of plant debris. The siliceous horizon may also locally represent root mats (Klappa, 1980).

*Facies Assemblage E.*—Facies Assemblage E is similar to assemblage D, except for more variability in coloration, relationship between ribbon and sheet sand bodies, paleosol characteristics and size of ribbon sand bodies. In general, sandstone is more abundant. Sandstone/mudstone ratios are generally 1.5-2.5, but can be as high as 3.5 or as low as 0.5. Sandstone sheets are typically less continuous laterally, although they do locally connect ribbons into tiers as in assemblage D (Fig. 4.2). Sandstone sheets are generally <1 m, although they are as much as 3 m thick, and can be traced for only several 10s of meters before they are lost due to erosional truncation. In a few locations sheet sandstones can be traced for ~1 km. Ribbons can be divided into small ribbons (<3 m) and large ribbons, locally as much as 18 m in thickness (Fig. 5). Small

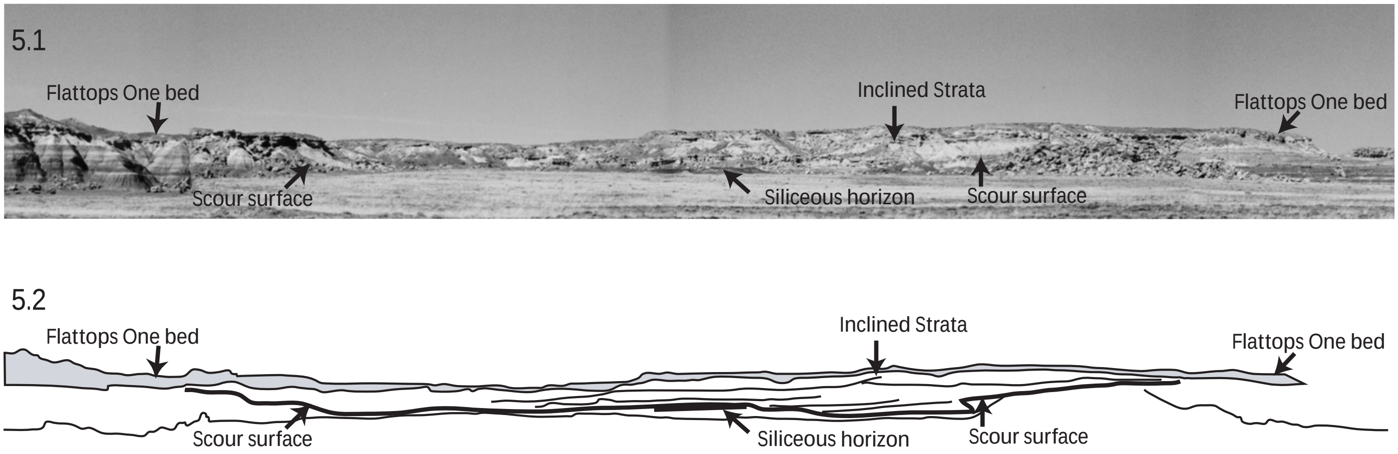

Figure *5*. Large sandstone with basal scour within facies assemblage E (Jim Camp Wash beds). Facies assemblage G (Flattops One bed) erosionally overlies the scour fill. Large-scaled inclined strata within the scour indicating probable lateral accretion are seen along the north (right) side of the sandstone body. *5.1*. photomosaic; *5.2*. line tracing.

ribbons have W/T <15, typically between 5 and 10. Large ribbons have W/T <20, typically 10-15. Granule- to cobble-sized gravel within ribbons is more common than in assemblage D, but is usually restricted to intraformational clasts, predominantly carbonate nodules. However, extraformational clasts are locally seen in high percentages, particularly within the large ribbons. Textural maturity is generally low, submature to immature, with large ribbons locally being mature (Woody, 2003). Sandstone is typically lithic wackes.

The sedimentary structures present are dependant upon the type of sandbody. Large ribbons possess the most variability in sedimentary structures, including very large- (>1 m), large- (15-100 cm), moderate- (5-15 cm), and small-scale (<5 cm) crossbedding, lateral accretion sets (Fig. 5), and rare ripple and horizontal laminations. Sedimentary structures are relatively rare in small ribbon and sheet sandstone bodies, but small- to moderate-scale crossbedding, and ripple and horizontal laminations were locally observed. Lateral accretions sets are locally common in thicker sheet sandstones. Petrified wood is locally common within large ribbons, and rarely within small ribbons. Wood is typically observed as trunk fragments ranging in size from 15 to 60 cm in diameter and 30 to 90 cm in length. *In situ* fragments were most commonly observed with their long dimensions perpendicular to the slope of inclined heterolithic strata.

Mudstone has the most variability within this assemblage. Individual beds are typically traceable for a few meters to a few 100s of meters. The most common coloration is purple, although green-gray, gray, red and dusky-blue are also common. Locally, green to black mudstone fills moderate to large scour-like features, such as in section Dry Wash North (Appendix A).

Complete paleosol profiles are rarely preserved. Where preservation allows assessment, profiles range from simple to composite (Kraus and Aslan, 1993; Marriott and Wright, 1993), with a majority being composite. Gray mottling is common, both along slickensides and root traces and less commonly within the matrix. Carbonate nodules are abundant in most localities (typically as *in situ* horizons) and commonly associated with slickensides and root traces. The presence of slickensides is variable with most locations having slickensides from 0.2-0.5 m in height, a few localities posses numerous slickensides >0.5 m. Ped structures are commonly poorly-developed, but are locally well-developed. Rhizoliths and rhizocretions, including carbonate and siliceous preservation, are common in certain horizons.

A discontinous horizon (0-30 cm thick) of siliceous material preserved in numerous depositional settings is seen 7-15 m above the top of facies assemblage C. Many exposures exhibit a dendritic pattern on the surfaces similar to that seen in the siliceous horizon found in assemblage D. Other locations exhibit increasing size and abundance of siliceous rhizoliths culminating in a nearly continuous horizon, similar to a silcrete horizon in morphology (Klappa, 1980; Wright and Tucker, 1991), or simply a horizon with a silcrete-like morphology. Creber and Ash (1990) also described silicified whole logs, branches and roots with a "rope-like" texture within this horizon.

Facies assemblage E is interpreted as floodplain, avulsion, and channel deposits. Large channels (>3m thick) commonly show evidence of high sinuosity by abundant and well-defined lateral accretion surfaces (Thomas et al., 1987; Brierley, 1996). Smaller channels exhibit almost no evidence of lateral migration (e.g., Bridge and Leeder, 1979; Friend et al., 1979). The poor sorting and channel geometry suggests that they were sinuous (Miall, 1985); however, Kraus and Gwinn (1997) described very similar channels that were relatively straight in planview, which is supported by the lack of evidence of lateral migration. The interpretation of avulsion deposits is supported by similarity in facies, geometry, and lateral and vertical associations to strata previously interpreted as representing avul-

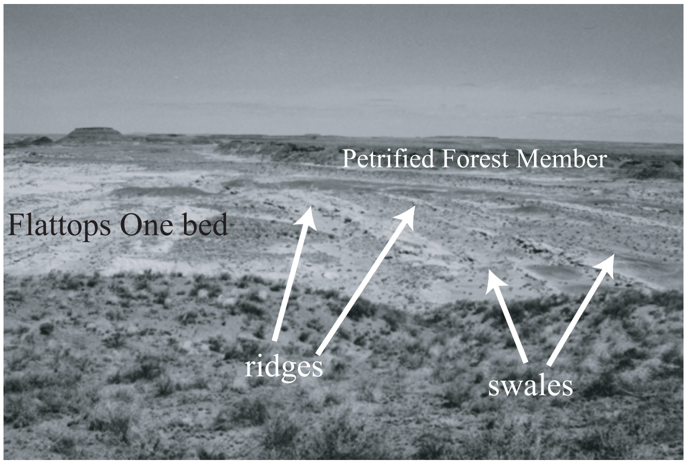

Figure *6*. Ridge-and-swale topography developed on the top surface of facies assemblage G (Flattops One bed) along the east rim of Jim Camp Wash.

sion deposits (Smith et al., 1989; Kraus and Wells, 1999; Slingerland and Smith, 2004).

A range in floodplain positions relative to the channel, from proximal to distal, is interpreted from lateral relationships and the high variability in pedogenic features, including slickenside abundance and size, matrix and mottling color and carbonate abundance, suggesting variation in both duration of pedogenesis and drainage conditions (e.g., Bown and Kraus, 1987; Kraus, 1987; Bown and Kraus, 1993; Aslan and Autin, 1998). The siliceous horizon was interpreted by Creber and Ash (1990) as an interval of increased silification due to increased pore space from a period of widespread fungal attack on plant material. These authors also commented on the potential regional stratigraphic utility this horizon.

*Facies Assemblage F.*—Medium- to coarse-grained sandstone and granule to cobble conglomerate and sandy conglomerate comprise facies assemblage F. Mudstone lenses are rare and make up less than 10% of any vertical section. Mudstone, where present, is generally dusky-blue or gray. Sandstone ranges from pale tan to moderate tan and light gray to yellowish gray on fresh surfaces and gray to brown on weathered surfaces. Sandstone is typically moderately- to well-sorted and texturally mature to submature, locally very mature (Woody, 2003). Conglomerate clasts range from granules (relatively rare) to cobbles. Chert clasts are the most widespread gravel-sized clasts and are typically white or orange, although brown and black clasts are locally present in small abundances. Quartzite clasts comprise a moderate percentage of clasts in most localities. Volcanic clasts are typically almost as abundant as chert clasts, and are often the largest in size within most given clast populations. Local sandstone clasts are also among the largest clasts present in a few areas. Intraformational clasts are rare and typically among the smallest gravel-sized clasts. Sandstones are lithic arenites to lithic wackes. Petrified wood is common in most locations as fragments of trunks ranging from ~15 cm to 1 m in diameter and ~20 cm to over 1 m in length (Ash and Creber, 1992; Heckert and Lucas, 1998b; Ash and Creber, 2000). Orientations of petrified logs are variable (Demko, 1995b; Ash and Creber, 2000).

The most common sedimentary structures in facies assemblage F are moderate- to very large-scale, planar crossbedding. Other sedimentary structures include local, small- to large-scale, trough cross-bedding, horizontal laminations, pebble imbrication and soft sediment deformation (Deacon, 1990; Woody, 2003). Deacon (1990) described local inclined bedding surfaces and levee deposits in the vicinity of Blue Mesa, and herringbone cross-stratification in the vicinity of Crystal Forest.

Sandbodies are sheet-like and multistoried (cf., Friend et al., 1979). Individual stories are 0.3-5m thick (typically ~1m) and are commonly separated by well-defined scours. Complex lateral and slightly vertical amalgamation patterns are indicated by the individual stories (Deacon, 1990; Woody, 2003). The assemblage typically holds up mesas and buttes and is well-indurated at most localities.

Large- to very large-scale, crossbedding, abundant gravel and consistent paleocurrent directions within individual stories suggest deposition of assemblage F by a braided stream (Miall, 1977; Miall, 1985; Brierley, 1996). Deacon (1990) interpreted the traditional Sonsela Sandstone bed (mostly facies assemblage F) as a large braided stream complex with well-defined linguloid and transverse bars. Local lateral accretion surfaces and increasing paleocurrent variability indicate that sinuosity increased slightly in the upper portion of the assemblage. Mudstone, as lenses and interbeds, is also more common in the upper part further supporting increasing sinuosity (e.g., Jackson, 1978; Miall, 1985; Miall, 1987).

*Facies Assemblage G.*—Facies assemblage G is comprised of fine- to coarse-grained sandstone, sandy conglomerate, and minor mudstone lenses. Gravel is predominantly carbonate nodule intraformational clasts, but locally in lenses includes large percentages (up to 70%) of volcanic and chert extraformational clasts. Chert clasts are generally brown, black, or white in color, in order of decreasing abundance. Orange chert clasts are rare. Quartzite is only locally present. Gravel ranges in size from granule to cobble, but is typically granule to pebble. Sandstone is poorly- to locally well-sorted lithic wackes to lithic arenites. Sandstone ranges in color from pale tan to brown and light to moderate gray on fresh surfaces. Weathered surfaces are generally yellow-tan to brown. Sandstone is typically either massive or has well developed moderate- to large-scale (5-15 cm and >15cm, respectively) crossbedding. Small-scale (<5 cm) crossbedding and horizontal laminations are locally common, typically in the upper portion of the assemblage. Petrified wood is locally common as trunk fragments typically ranging from 10-75 cm (locally up to 2 m) in diameter and 20 cm to several meters in length. The orienta-

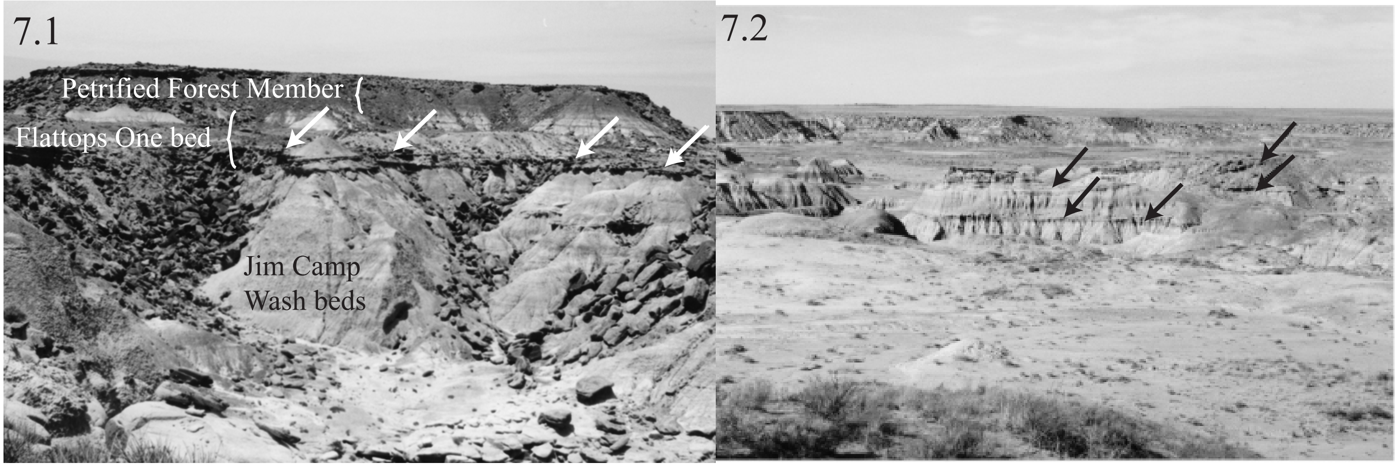

Figure *7*. Complex internal architecture of facies assemblage G (Flattops One bed). *7.1*. Sandstone and conglomerate of facies assemblage G (Flattops One bed) with irregular scouring between individual beds suggesting fluctuations in local base level and possible localized and small-scale (under 2°) tilting from salt tectonism. Mountain Lion Mesa; *7.2*. Sandstone and conglomerate lenses within lower part of facies assemblage G (Flattops One bed) indicating rapid fluctuations in local base level. East rim of Jim Camp Wash.

tion of the petrified wood is variable but is typically perpendicular to paleocurrent direction. The upper part of the assemblage possesses common inclined bedding surfaces and local ridge-and-swale topography (cf., Nanson and Page, 1983; Fig. 6).

Sandbodies have sheet-like morphologies (cf., Friend et al., 1979) and are often multistoried. Individual stories are typically defined by shallow scour surfaces and range from 0.25-5 m thick (typically ~0.75 m). Thin mudstone lenses locally separate stories and even sandbodies in some instances. Locally complex architecture similar to that reported by Blakey and Gubitosa (1984) and Hazel (1991) in the Salt Anticline region of Utah is seen between stories or between thin sheets separated by mudstone (Fig. 7). Sandstone is generally moderately- to well-indurated and holds up mesas and buttes. However, in a few locations the assemblage is relatively incompetent and forms rounded ridges.

Mudstone lenses can comprise up to 40% of the vertical section. In these areas the assemblage appears as a series of sandstone lenses similar to those of assemblage E. The boundary between assemblages E and G are difficult to determine in these locations. However, the sandstone lenses included in facies assemblage G have W/T ratios greater than ~30, distinguishing them from those in assemblage E. Mudstone is variable, similar to facies assemblage E, although gray is the most common color in assemblage G, further distinguishing the two assemblages. Typical mudstone contents of the facies assemblage range from 5-25%.

Facies assemblage G is interpreted as the deposit of a low- to at least moderate-sinuosity bedload stream. Like assemblage F, sinuosity appears to increase upsection, although in this assemblage it reaches a level where ridge-and-swale topography developed. Paleocurrent variability (Espegren, 1985; Woody, 2003) also supports low to moderate sinuosity. The stream system appears to be smaller than the one responsible for deposition of facies assemblage F as indicated by the finer average grain size, smaller largest and average gravel size, thinner stories, and smaller crossbedding. The more easterly flow direction and the smaller nature of the stream than the facies assemblage F stream system is interpreted as evidence that assemblage G was deposited by a tributary system to the large trunk channel belt of facies assemblage F. Deacon (1990) interpreted the confluence of a tributary system with the main trunk system of the traditional Sonsela (facies assemblage F) in the vicinity of Crystal Forest. Woody (2003) also described interfingering of facies assemblages F and G in the Crystal Forest area further supporting the interpretation of a trunk and tributary system, respectively.

*Facies Assemblage H.*—Facies assemblage H consists of predominantly mudstone with several laterally persistent sandstone bodies. Sandstone outside of the laterally persistent bodies is rare. The sandstone is fine- to medium-grained and poorly- to moderately-sorted. Sandstone is typically reddish gray on fresh surfaces, but is locally light gray. Weathered surfaces are generally brown or grayish-red. Gravel is rare and is almost exclusively intraformational carbonate nodule clasts. Small- to moderate-scale crossbedding is more common than large-scale crossbedding and lateral accretion sets are prevalent (e.g., Espegren, 1985).

Mudstone is predominantly deep purple or red with moderate to abundant gray mottling and large (>0.5 m) slickensides and vertically oriented columnar peds. Local clay-rich lenses are dusky blue to green and generally lack paleosol features, such as mottles and slickensides. Carbonate nodules are prevalent and well-developed. Paleosol profiles are typically thick and compound or composite with well-developed vertic features (Zuber, 1990; Marriott and Wright, 1993). Individual units can typically be traced for several kilometers, ex-

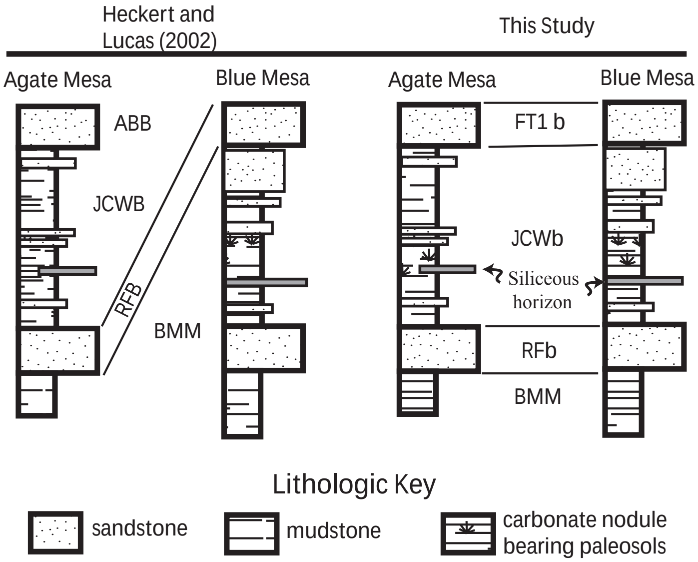

Figure *8*. Schematic stratigraphic sections at Agate Mesa and Blue Mesa emphasizing the inconsistencies in correlation between this study and that of Heckert and Lucas (2002b). Both sections approximately are 40 m in thickness. Note the presence of the unique siliceous horizon in both sections and the similarity of facies and facies associations below the capping sandstones. BMM=Blue Mesa Member; RFB=Rainbow Forest Bed; RFb=Rainbow Forest beds; JCWB=Jim Camp Wash Bed; JCWb=Jim Camp Wash beds; ABB=Agate Bridge Bed; FT1b=Flattops One bed.

cept for where locally truncated by "gully systems" (Kraus and Middleton, 1987).

A well-drained landscape of well-developed floodplain paleosols is interpreted from the mudstone coloration, slickensides and carbonate nodules (e.g., Driese and Foreman, 1992; Kraus, 1999). The textural immaturity, abundance of lateral accretion sets, shallow-based geometry and dearth of gravel supports the interpretation of the sandstone bodies as being deposited by high-sinuosity streams laterally migrating across the well-drained floodplains (e.g., Brierley, 1996; Bristow, 1996).

## STRATIGRAPHY

As shown in Figure 2.2, there is no consensus as to what units have been assigned to the Sonsela Sandstone bed or to the relationship of related units throughout PEFO, much less regionally. As outlined above, the Sonsela has typically been associated with large sandstone bodies, partially due to the nomenclatural terminology of the Sonsela being restricted to a sandstone "bed". Mudstone intervals that are clearly associated with the Sonsela are usually either disregarded or placed within the upper or lower part of the Petrified Forest Formation (Billingsley, 1985; Billingsley et al., 1985; Deacon, 1990; Long and Murry, 1995; Heckert and Lucas, 1998b), resulting in ambiguity in the placement of the upper and lower contacts of the Sonsela and difficulty in regional correlation.

Heckert and Lucas' (2002b) revision of the Sonsela solves some of these problems by addressing the relationship between sandbodies and associated mudstone. Heckert and Lucas (2002b) noted the similarity of the PEFO section to that of the Sonsela type section with a medial mudstone unit separating lower and upper sandbodies; however, they did not provide a map detailing the geographic distribution of their units, in contradiction of the practices outlined by the NACSN (1983), and they did not provide robust descriptions of their subunits that would allow recognition outside of the immediate vicinity of PEFO. These two facts leave ambiguity in the identification of the Sonsela both regionally and within PEFO. Cooley (1957) and Roadifer (1966) commented on the presence of multiple beds assignable to the Sonsela in the region immediately adjacent to PEFO and the revisions of Heckert and Lucas (2002b) do not address how to recognize or interpret such beds as tongues, lenses, etc., or where they would fit within their nomenclature of a tripartite subdivision.

In fact, even within PEFO, the correlations of Heckert and Lucas (2002b) are not consistent, either stratigraphically or lithologically. For example, they cite their uppermost unit (Agate Bridge Bed) as the capping sandstone of Agate Mesa, but their lowest subunit (Rainbow Forest Bed) as the capping sandstone of Blue Mesa (Fig. 8). Mapping during this study (Fig. 9) shows that the capping sandstone of both of these mesas is laterally equivalent (Fig. 8), in agreement with numerous other workers (Cooley, 1957; Roadifer, 1966; Billingsley et al, 1985; Espegren, 1985; Murry, 1990; Long and Murry, 1995). Lithologic correlation of facies on the mesa faces and of the capping sandstones themselves also supports the correlation presented in this study (see below).

The following nomenclature is proposed to provide a regionally consistent framework upon which to base future studies, honor nomenclatural traditions of previous workers, and to conform to the guidelines of the North American Stratigraphic Code (NACSN, 1983). In agreement with numerous previous workers (Stewart et al., 1972a; Stewart et al., 1972b; Blakey and Gubitosa, 1983; Dubiel; Lehman, 1994; Demko, 1995b; Demko et al., 1998), the Chinle is retained as a formation in this study based on my interpretation that the bounds of the Chinle as a fundamental unit (formation) delimit the "surfaces of lithic change that give it the greatest practicable unity of constitution" (NACSN, 1983, Article 24 (a)). Retaining the name Chinle Formation does not negate recent advances in biostratigraphic, lithostratigraphic and chronostratigraphic correlation with other Upper Triassic units of the Western Interior (e.g., Long and Murry, 1995; Lucas et al., 1997; Lucas, 1998; Steiner and Lucas, 2000), *contra* Lucas and colleagues (e.g., Lucas et al., 1994; Lucas et al., 1997; Heckert and Lucas, 2002b). Concerns over the recognition of these recent advances should not outweigh the "distinctive lithic characteristics" for which lithostratigraphic units are named and utilized (NACSN, 1983, Article 24 (c)).

The assignment of facies assemblages to stratigraphic units adheres to the guidelines of the NACSN (1983), by describing specific lithologic characters that are the basis for the lithostratigraphy proposed herein. The facies assemblage descriptions are combined and discussed to delimit characteristic features and the lateral variability of those diagnostic features. It is my opinion that this method provides the most robust description of units and justification of inclusion, or exclusion, of subunits and lateral equivalents.

## Blue Mesa Member

The Blue Mesa Member corresponds to facies assemblage A of this study. The term Blue Mesa Member is used in the capacity of Lucas (1993) to replace the term "lower" Petrified Forest Member; however, the Blue Mesa Member is here modified from its original definition (Lucas, 1993) to exclude units 16-20 of the type section, yielding a modified thickness of 57+ meters. There have been recent arguments about whether or not the base of the PEFO section contains strata below the Blue Mesa Member (Heckert and Lucas, 1997; Heckert and Lucas, 1998a; Dubiel et al., 1999; Therrien et al., 1999; Hasiotis et al., 2001), thus possibly further reducing the type section of the Blue Mesa Member. Complex interfingering of the Shinarump, Bluewater Creek, and Mesa Redondo Members would be expected in northeastern Arizona based upon the reports of Cooley (1957, 1958, 1959) and Stewart et al. (1972b). While preliminary examination did show lithologies similar to the upper two-thirds of the Mesa Redondo Member and the lower red member (=Bluewater Creek Member of Lucas and Hayden, 1989) as described by Cooley (1957, 1958), Lucas and Hayden (1989) and Heckert and Lucas (1998a, 2002a, 2002b), this study did not examine this lowest part of the stratigraphic section in enough detail to warrant its exclusion from, or inclusion within, the Blue Mesa Member at this time.

The Blue Mesa Member, as revised herein, is a sequence of blue-gray, dusky-blue, purple and locally green, yellow and red mudstone with local, relatively thin sandstone bodies that lies stratigraphically below the Sonsela Member. The typical outcrop expression is steep to rounded ridges and knolls of dusky-blue to purple bentonitic mudstone. Mudstone generally shows evidence of moderate to extensive pedogenesis by mottle and carbonate nodule development. The traceability of individual mudstone units is variable, although most are only traceable for distances between 50 and 500 m where topography permits. Many units seem to fill broad scours (e.g., Repenning et al., 1969).

Sandstone bodies are typically less than 0.5 m thick, and rarely over 1 to 3 m thick. Sandstone body geometries are typically sheet-like with width/thickness ratios (W/T) >50-100. Locally sandstone bodies have W/T ~15-25 and fill shallow scours. True ribbons (cf., Friend et al., 1979) are rare.

*Discussion*.— The nomenclature of the interval below the Sonsela Member within PEFO is somewhat ambiguous. The term Blue Mesa Member is preferred over the term "lower" Petrified Forest Member due to its distinctive lithology and distribution, long recognized in the literature (Cooley, 1957; Akers et al., 1958; Stewart et al., 1972a, 1972b), warranting member status. The Blue Mesa has been equated, at least in part, to the Monitor Butte Member of southern Utah based upon molluscan fauna and some lithologic similarities (Good, 1993). The author does not agree with some recent assertions that the Monitor Butte should be extended to the PEFO area and up to the base of the Sonsela Member (e.g., Dubiel et al.,

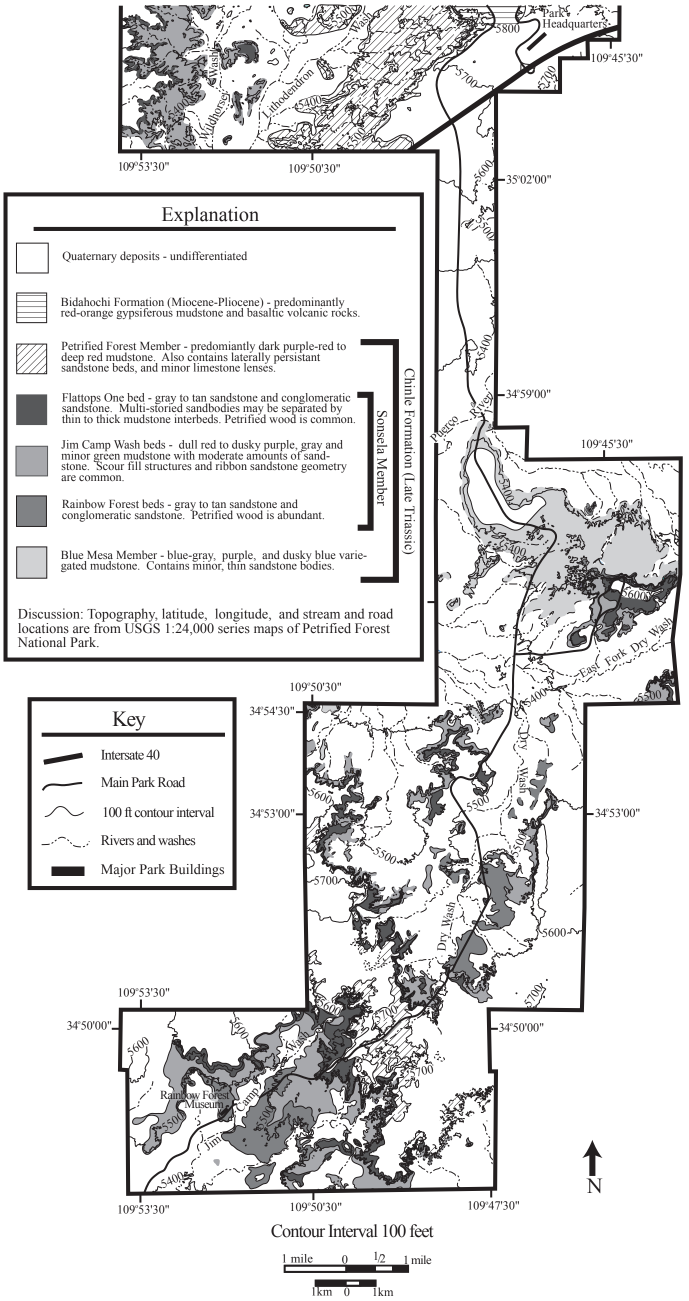

Figure *9*. Preliminary geologic map of the southern part and the Devil's Playground region of PEFO. Mapping was completed at a scale of 1:24000 and reduced for display here. Full scale map is in Woody (2003).

1999; Hasiotis et al., 2001) for the following reasons: 1) The lithologies that are similar between the Monitor Butte and Blue Mesa Members are not a dominant portion of either member and most likely reflect ephemeral and/or local depositional environments as expected in a complex fluvial environment (Therrien, 1999). In fact, a complex interfingering relationship between the two members has been observed in other areas where the Blue Mesa Member (= "lower" Petrified Forest Member) overlies the Monitor Butte Member, such as in the southern Monument Valley (Repenning et al., 1969; Lucas et al., 1997). 2) The Monitor Butte in Utah has traditionally been associated with Gregory's original Division D, which is near the base of the formation (Stewart et al., 1972a, 1972b). Stratigraphic units at the base of the Chinle Formation or immediately above the Shinarump Conglomerate when it forms the base of the Chinle Formation, i.e., the lower red member (=Bluewater Creek of Lucas and Hayden, 1989), Mesa Redondo Member, and Monitor Butte Member, have historically been excluded from Gregory's original Division C (=Petrified Forest Member of Gregory 1950) due to either stratigraphic position or lithology. Division C (=Petrified Forest Member) is typically noted as being more mud dominated and variegated than units below (Gregory, 1950; Stewart et al., 1972a, 1972b), which is the case in the region surrounding PEFO. My opinion is that combining the nomenclature of divisions C and D, as currently understood, would add more confusion to analyses of the depositional history than it would clarify relationships. 3) The "lower" Petrified Forest Member (=Blue Mesa Member) interval has a long history of recognition as a distinct lithologic entity, both regionally and stratigraphically, in the literature (Cooley, 1957; Akers et al., 1958; Stewart et al., 1972b). In the outcrop belt described here, the "lower" Petrified Forest Member can be distinguished from the Monitor Butte Member based upon lithologic criteria, warranting separation under the NASC (NACSN, 1983). Additionally, the history of usage indicates that there is utility in distinguishing between the "lower" part of the Petrified Forest Member and the Monitor Butte. Continuity precludes dropping the separation where it is not necessary for clarity and consistency, which is accomplished by using the term Blue Mesa Member for the strata in PEFO and other areas.

The Blue Mesa lithology as described above is limited in outcrop distribution to a relatively narrow band running north-northwest from the Arizona-New Mexico border south of St. Johns, Arizona to the Cameron, Arizona area and north to the Utah-Arizona border. This distribution of the Blue Mesa Member either indicates a limited distribution of depositional environments responsible for the deposition of the Blue Mesa or defines the erosional extent of the Tr-4 unconformity as described by Heckert and Lucas (1996). The Tr-4 unconformity was proposed by Lucas (1993) to describe the erosional basal surface of the Sonsela Member and the local absence of the underlying strata, i.e. the Blue Mesa Member, in areas such as the Zuni Mountains and southeastern Utah as documented by previous workers (Stewart et al., 1972b; Blakey and Gubitosa, 1983; Lucas and Hayden, 1989; Dubiel, 1994). The unconformity was postulated to span a 1-2 Ma time span based upon faunal differences in strata above and below the surface. However, as has been discussed above, this study indicates that the basal surface of the Sonsela is related to the deposition of several individual sheet sandbodies, and even within the relatively small confines of PEFO is not as a single continuous erosional surface. Thus, the Tr-4 unconformity must either be limited in distribution to areas to the north and west of PEFO, or is not a regionally significant surface.

## Sonsela Member

The Sonsela Sandstone bed and associated lithologic packages previously not recognized, warrants increase in rank to member status (Lucas, 1993) based upon its distinctive and recognizable lithologies and distribution (NACSN, 1983). Lucas (1993) originally raised the Sonsela to a member when he raised the rank of the Chinle Formation to the Chinle Group; however, no specifics of lithology or variation were noted to support the elevated rank. Heckert and Lucas (2002b) retained this nomenclature when they recently revised the stratigraphy of PEFO.

The unit, as redefined herein, can be distinguished by its moderate to high sandstone/mudstone ratios, cut-and-fill architecture, abundance of thin and thick (<3 m and >3 m, respectively) ribbon sandstone bodies, lateral extent of local sandstone bodies, conglomerate clast compositions (abundant volcanic clasts and to a lesser extent chert and quartzite clasts), variability in mudstone characteristics (where present), abundance of heterolithic deposits of alternating sandstone and mudstone within muddy intervals, and stratigraphic position. No other unit within the Chinle Formation in the vicinity of PEFO possess this complete list of features, although some of the features may be found in isolated sand bodies or as isolated lenses. Other coarse-grained units within the Chinle, such as the Shinarump Conglomerate and Moss Back Member, differ in having lower mudstone contents, less variability in mudstone characteristics (where it is present), different clast compositions, rare heterolithic deposits, a general lack of widespread cut-and-fill architecture on a small and large scale, and lack of association of several different horizons of lenticular sandstone. The Shinarump and Moss Back also appear to posses locally deep scours (locally several tens of meters) at their bases which are generally not present at the base of the Sonsela and its associated sandstones (Stewart et al., 1972b; Blakey and Gubitosa, 1984). Finer-grained units in the Chinle differ from the Sonsela Member in the low sandstone/mudstone ratios, general lack of thick, well-consolidated sandstones, particularly ones with large-scale crossbedding, general absence of sheet sandstone bodies, and a lack of variability in mudstone characteristics on short horizontal scales.

Facies assemblages B through G are included within the Sonsela Member. The Sonsela Member comprises all Upper Triassic strata geographically located in PEFO between Blue Mesa and The Flattops (Fig. 3; Fig. 9), and a majority of the Upper Triassic strata south of The Flattops (Woody, 2003; Fig. 9). Paleocurrents are predominantly to the north and northeast, and sometimes east, in contrast to other members of the Chinle Formation, which generally have a northwesterly transport direction (Akers et al., 1958; Stewart et al., 1972b; Espegren, 1985; Deacon, 1990; Woody, 2003). Sections Blue Mesa 1 and Mountain Lion Mesa 1 are provided as reference sections for the Sonsela Member (Appendix A).

As recognized by Heckert and Lucas (2002b), the Sonsela Member within PEFO consists of a tripartite subdivision of a lower sandstone interval, a medial mudstone and sandstone interval, and an upper sandstone interval. This subdivision is similar to that found at the type section, as well as other regions of the Colorado Plateau (Akers et al., 1958; Heckert and Lucas, 2002a). Nomenclature for the individual subdivisions is proposed that differs from that proposed by Heckert and Lucas (2002b) because of differences in stratigraphic and lithologic correlation (Fig. 8) and the importance given to the maintenance of utility and tradition of past literature. Informal nomenclature is preferred here due to problems with regional recognition, which are attributable to local absences and rapid lateral facies changes (e.g., Cooley, 1957; Roadifer, 1966; Woody, 2003), and thus limiting regional utility. The lower sandstone interval is referred to as the Rainbow Forest beds, the medial mudstone and sandstone interval is referred to as the Jim Camp Wash beds, and the upper sandstone interval is referred to as the Flattops One bed.

*Rainbow Forest beds.*—The Rainbow Forest beds are the lowest subdivision of the Sonsela Member within PEFO. The unit includes Cooley's (1957) Rainbow Forest sandstone, which comprises most of the unit in the southern part of PEFO near the Giant Logs and Long Logs forests (facies assemblage C). The Camps Butte sandstone of Murry (1990) (more properly referred to as the Camp Butte sandstone) comprises the unit in more northerly parts of PEFO south of I-40 (facies assemblage B). The two sandstones were traced to a point of mutual pinchout at Lots Wife (north of Agate Mesa), with the pinchout of the Rainbow Forest sandstone of Cooley overlying the pinchout of the Camp Butte sandstone by approximately 30 cm (Woody, 2003; Fig. 10). The close stratigraphic proximity of the two sand bodies and similar details of geometry, architecture and lithology warrant inclusion within the same lithostratigraphic unit and support interpretation of a similar depositional history. The unit was either not observed in the Devil's Playground area or has a slightly different nature that eluded recognition, highlighting some of the difficulties in regional correlation of individual subunits of the Sonsela Member (see Woody, 2003), and supporting their retention as informal units.

Facies assemblages B and C are here included within the Rainbow Forest beds. I feel that more utility is garnered by lumping the two facies assemblages and their respective informal nomenclature together, because they are very closely spaced stratigraphically and similar in lithology and sedimentary structure, indicating a similar genetic history. The Rainbow Forest beds are defined as the first large, laterally-persistent sandstone body or stratigraphically closely spaced series of sheet-like, multi-storied sandstone bodies possessing significant volcanic and/or chert extrabasinal clasts at the base of the Sonsela Member. Cooley's (1957) section is considered the type of the beds. Sections Lots Wife, Old 180 W, Blue Mesa 1 and Camp Butte are given as reference sections (Appendix A). Colors range from gray to maroon but are typically light (light gray to pale tan or pinkish gray). Mudstone is typically rare, but is more common near the top of the unit. The Rainbow Forest beds are typically 3-10 m thick, but were locally observed to be over 15 m thick. In some areas the top of the unit is difficult to determine due to interfingering with the overlying Jim Camp Wash beds and poor exposure.

Sandstone within the Rainbow Forest beds is typically medium-grained but ranges from fine- to coarse-grained. Conglomerate is locally abundant, with as much as 70% being extrabasinal volcanic clasts. Sandbodies are typically multi-storied with scoured surfaces separating individual stories, and they are moderately to well-indurated. Individual stories have W/Ts that are generally less than the sand bodies as a whole (20-30; rarely up to 50). Petrified wood is pervasive. The brightly-colored petrified wood deposits at Giant Logs, Long Logs and Crystal Forest (Fig. 3) are all located within the Rainbow Forest beds.

The Rainbow Forest beds exhibit an erosional relationship with the underlying Blue Mesa Member. Scours are typically broad and shallow. Deacon (1990) reported scours with as much as 7 m of local relief at the base of the Sonsela, but it is unknown by the author if the scours in question were in the Rainbow Forest beds as used here or in another unit of the Sonsela, such as the large ribbons in the Jim Camp Wash beds discussed below. The scours appear to be associated with the depositional sequence responsible for the overlying sand body rather than being of regional significance. The Rainbow Forest beds grade into and locally interfinger with the overlying Jim Camp Wash beds.

The Rainbow Forest beds can be distinguished from the underlying Blue Mesa Member by the more texturally mature nature of sandstone (to a lesser extent by the compositional maturity), the local presence of coarse- to very coarse-grained sandstone, the presence of large percentages of extrabasinal clasts (particularly the locally abundant volcanic clasts), predominance of preserved large-scale crossbedding, and sheet-like nature. The Rainbow Forest beds can be distinguished from the Jim Camp Wash beds by the sheet-like nature, greater percentage of extrabasinal clasts, lower percentages of mudstone, and lack of variability in mudstone coloration. The Rainbow Forest beds can be distinguished from the Flattops One bed by the generally lighter color, greater percentage of volcanic gravel-sized clasts and greater distribution of brightly-colored petrified wood in the Rainbow Forest beds, and position between the Jim Camp Wash beds and the Blue Mesa Member.

*Jim Camp Wash beds*—The Jim Camp Wash beds are the medial muddy interval of the Sonsela Member as defined in this study. The term Jim Camp Wash beds is used here in the sense of Heckert and Lucas (2002b), except for a preference for informal nomenclature (see above). Revisions are made to the definition to clarify lithologic variability within the unit and distinguish the unit on lithologic criteria that will allow for more utility when conducting regional studies.

Similarity of features and lateral equivalence has led to the inclusion of facies assemblages D and E within the Jim Camp Wash beds. Although mudstone in facies assemblage D is more common than in most facies assemblage E sections, the mudstone/sandstone ratios are still anomalous for Chinle strata outside of the Sonsela Member in the vicinity of PEFO. The facies architectures of prevalent ribbon and thin sandstones surrounded by mud and silt with complex cut-and-fill architecture are also more similar between facies assemblages D and E than to any other portion of the Chinle Formation. However, Heckert and Lucas (2002b) assign the interval included within facies assemblage D to the Blue Mesa Member and within facies assemblage E to the Painted Desert Member of their Petrified Forest Formation (= "upper" Petrified Forest Member of Akers et al., 1958, Stewart et al., 1972b; Billingsley, 1985; Billingsley et al., 1985; see Fig. 3). In the area west and south of Agate Mesa (Fig. 3) facies assemblages D and E were found to grade into one another allowing strict stratigraphic correlation, supporting the interpretation made by lithologic comparisons that they are related units. The presence of the unique siliceous horizon in both facies assemblages also supports the correlations proposed here.

The Jim Camp Wash beds are herein defined as a heterogenic sequence of mudstone, sandstone and conglomerate possessing numerous ribbon and thin sheet sand bodies, local large ribbon sand bodies and high degrees of variation in color, grain-size, and morphological features within mudstone units located between the sand- and conglomerate-dominated Rainbow Forest and Flattops One beds. The type section is maintained as units 3-6 of the Giant Logs section of Heckert and Lucas (2002b). Sections Agate Mesa West 1, Mountain Lion Mesa 1, Dry Wash North and Blue Mesa 1 (Appendix A) are proposed as reference sections to show lateral variability. The unit can be distinguished from other units of the Chinle Formation by its nearly equal percentages of sandstone and mudstone, prevalence of sandstone ribbons with deeply scoured bases, common heterolithic intervals, lateral variability in coloration, and general lack of lateral continuity of facies. The unit is typically between 20 and 40 m thick. The disparity in thickness is largely the result of variations in the thickness of the underlying Rainbow Forest beds and the overlying Flattops One bed. The Jim Camp Wash beds can be distinguished from other units of the Sonsela by its higher mudstone content, prevalence of ribbon sandstone architecture and position between laterally extensive sheet sandstones (i.e., the Rainbow Forest and Flattops One beds).

The Jim Camp Wash beds may be the most distinctive unit of the Sonsela Member and be useful in regional identification, particularly where the lower, upper, or both, sandy intervals may be absent. The near equal percentage of sandstone and mudstone (ratios ranging from 0.5 to 2.5, but typically 1.5) is unique in the Chinle Formation in the vicinity of PEFO. The combination of cut-and-fill architecture, abundance of heterolithic deposits, wide lateral variability in mudstone characteristics, sandstone "tiers", presence of small and large ribbon- and thin sheet-sandstone bodies in close lateral and stratigraphic proximity, and the siliceous horizon also appear to be distinctive.

Large ribbon sandstone and conglomeratic bodies can be confused with the sandstone and conglomerate of the Rainbow Forest and Flattops One beds because of similarity in composition and internal architecture. The large ribbon sandstone bodies of the Jim Camp Wash beds can be distinguished by the low W/T, more prevalent and deeper basal scours, dearth of multiple stories and lateral contiguity with mudstone units that match the description of the Jim Camp Wash beds. The mudstone units of the Jim Camp Wash beds can be distinguished from those of the Rainbow Forest and Flattops One beds by their greater abundance and variability in coloration, more abundant purple and red, predominant cut-and-fill architecture, abundance of heterolithic deposits, and thin, interbedded sheet sandstone bodies.

Creber and Ash (1990) first noted the presence of the siliceous horizon between the Rainbow Forest and Flattops One intervals and commented on its stratigraphic potential. They also found the horizon at a similar stratigraphic position in Texas, Utah and elsewhere in northeastern Arizona, and describe it as the result of an interval of increased fungal attack on plants during the Late Triassic. I also observed the layer in a similar position above a possible Rainbow Forest beds equivalent near Paria, Utah (see Woody, 2003). Unfortunately, the cut-and-fill architecture of the Jim Camp Wash beds has locally removed this horizon so that it is typically seen as a discontinuous horizon, limiting its local utility. However, the recognition of a single interval of increased siliceous preservation in areas as dispersed as Arizona, Texas, and Utah suggests that this layer may prove useful in identifying intervals stratigraphically equivalent to the Jim Camp Wash beds in other Upper Triassic strata in the western United States.

*Flattops One bed* —The Flattops One bed is the uppermost sandstone interval of the Sonsela Member at PEFO. Roadifer (1966) originally defined three Flattops sandstones above his "Jim Camp Wash zone" in the "upper" Petrified Forest Member. Roadifer mentioned that the Jim Camp Wash zone had a sandstone body that was more prominent than the rest and capped the mesa "north of Highway 260 (now Highway 180), just west of the south entrance to the Park" (Roadifer, 1966, p. 23). Billingsley (1985) defined four Flattops sandstones, with Flattops sandstone #1 being the lowest persistent sandstone within the "upper" Petrified Forest Member. This study indicates that the Flattops sandstone #1 as mapped by Billingsley et al. (1985) encompasses a ~10 m thick interval, including the mesa north and west of the Rainbow Forest Museum (i.e. the mesa of Roadifer's Jim Camp Wash zone). It would appear by the descriptions of Roadifer and the observations presented here that Flattops sandstone #1 of Billingsley et al. is probably the same unit as Roadifer's Jim Camp Wash zone (Heckert and Lucas, 2002b). Most workers subsequent to Billingsley (1985) have used his terminology (e.g., Espegren, 1985; Ash, 1987; Long and Murry, 1995; Therrien and Fastovsky, 2000), which will be followed here.

Flattops Sandstone #1 (*sensu* Billingsley, 1985; Billingsley et al., 1985) was named the Agate Bridge Bed by Heckert and Lucas (2002b) and revised to include the traditional Sonsela Sandstone bed that caps Agate Mesa. Espegren (1985) commented on the fact that the Flattops sandstone #1 bed was more similar to outcrops traditionally identified as the Sonsela than it was to the other Flattops sandstones. I disagree with Heckert and Lucas (2002b) that the term "Agate Bridge Bed" is preferable to the more engrained term "Flattops One". The type section of the Agate Bridge Bed is located near the Rainbow Forest Museum where the term Flattops One has had a long history of usage (Billingsley, 1985; Billingsley et al., 1985; Espegren, 1985; Long and Murry, 1995; Therrien and Fastovsky, 2000). The only difference in the usage of Heckert and Lucas (2002b) is to correlate the unit to outcrops traditionally associated with the Sonsela, such as at Agate Mesa. However, as has been previously discussed, this study has found that the Flattops One interval is correlative to the sandstone on top of both Agate and Blue Mesas.

It is my opinion that maintaining tradition of usage and only clarifying relationships provides more utility to future workers than a litany of nomenclatural designations. Refining the definition of the Flattops One bed to include these very similar (see below) and likely interfingering regions traditionally assigned to either the Sonsela Sandstone bed or the Flattops sandstone #1 provides stability to the nomenclature while enhancing its utility. Additionally, confusion would be avoided if new outcrops are discovered that change the interpretation of the relationship of these beds, or regional relationships contradict the recent findings of this study or Heckert and Lucas (2002b).

Flattops One bed includes facies assemblages F and G and is here defined as a series of closely spaced, laterally extensive, sheet-like deposits of multistoried sandstone and conglomerate (of both extrabasinal and intrabasinal origin) with prevalent internal scours and minor sandstone and mudstone lenses that directly overlie the Jim Camp Wash beds and underlie the Petrified Forest Member (as restricted below). The overall architecture is of laterally and slightly vertically amalgamated channel complexes (Deacon, 1990; Woody, 2003). Section Mountain Lion Mesa 1 is proposed as the type section. Sections Blue Mesa 1, Agate Mesa West 1, Old 180 4, Crystal Forest and Dry Wash are given as reference sections (Appendix A). The Flattops One bed ranges in thickness from ~5-20 m.

All of the sandbodies mapped by Billingsley et al. (1985) possess sheet-like morphologies and similar lithologies, and thus are interpreted as being genetically related. These sandbodies are included in facies assemblage G. Laterally equivalent units capping Agate Mesa and Blue Mesa (*contra* Heckert and Lucas, 2002b; see Figs. 8 and 9) have been included in facies assemblage F. The two facies assemblages appear to slightly inter-tongue in the Crystal Forest area, with facies assemblage F being more prevalent in the northern portion. Facies assemblage F possesses an unconformable relationship with underlying assemblages D and E, while facies assemblage G possesses either an unconformable or gradational basal contact depending on location. Characteristics of lateral continuity, alluvial architecture, sedimentary structures, general lack of mudstone, sandstone composition and texture and stratigraphic position can be used to distinguish these two facies assemblages from other units of the Chinle Formation, and thus warrant their inclusion within the same lithostratigraphic unit.

Support of the inclusion of the Flattops One bed within the Sonsela Member comes from high percentages of sandstone, alluvial architecture of sheet sandstones with dominant large- to moderate-scale crossbedding and internal scouring between stories, and presence of relatively high percentages of extrabasinal clasts. Distinction between the Rainbow Forest beds and the Flattops One bed can be difficult. The most ubiquitously observed criterion is stratigraphic location within the Sonsela Member. Where that criterion is not ascertainable, then designation of the Flattops One bed should be made by its tendency to be tan in color rather than light gray, tendency to be more indurated, less abundant volcanic clasts relative to chert clasts, more common intrabasinal clasts (although intrabasinal clasts are locally absent), thinner average story, greater abundance of internal scour, greater evidence of lateral amalgamation, more common mudstone lenses in the lower and upper portions relative to the middle portion, and the prevalence of gray mudstone rather than dusky blue mudstone. The Flattops One bed can be distinguished from the Jim Camp Wash beds by its greater percentages of sandstone, greater lateral continuity of large sandstone bodies (W/T >30), greater evidence of lateral amalgamation (cf., Bridge and Leeder, 1979; Friend et al., 1979), predominance of multiple stories within sandbodies, tendency to be better lithified, dominance of gray mudstone (where present) and lack of lateral variability of mudstone units. Even though the sandstone bodies that comprise the Flattops One bed have basal scours, the unit largely grades into the underlying Jim Camp Wash beds, particularly south of Mountain Lion Mesa, making the lower contact difficult to identify in some sections. The base of the Flattops One bed should be placed at the first multistoried sandbody possessing W/T ratios in excess of 30. The contact should be considered interfingering where sandstone lenses or tongues meeting the above description are overlain by mudstone with high degrees of variability and/or possesses abundant sandstone ribbons with W/T <15. The Flattops One bed can be distinguished from the Flattops sandstones in the Petrified Forest Member by its lighter coloration (gray to tan, rather than reddish gray), greater abundance of extrabasinal clasts, internal architecture, generally coarser nature, average paleocurrents to the east and north as opposed to northwest (Espegren, 1985; Woody, 2003) and its position at the top of the Jim Camp Wash beds.

### Petrified Forest Member

The Petrified Forest Member has previously been divided into a "lower" and an "upper" portion (Cooley, 1957; Akers et al., 1958; Stewart et al., 1972a, 1972b), which included all of the previously described strata. The author here restricts the use of the term Petrified Forest Member in the immediate vicinity of PEFO to include only the "upper" portion as used by previous workers. Lucas (1993) proposed the term Painted Desert Member of the Petrified Forest Formation for the same strata when he elevated the Chinle to group status. However, the term Painted Desert Formation was originally used to describe a portion of what is now the Glen Canyon Group (Ward, 1905; Darton, 1910; Repenning et al., 1969; Stewart et al., 1972a). The author feels that a restriction of a widely used term rather than the reuse of an antiquated term will cause the minimal amount of confusion when adapting the new nomenclature. Additionally, the restriction of the Petrified Forest Member in the vicinity of PEFO would corroborate with its usage and described lithology throughout much of the outcrop belt, including the type section.

Although the Petrified Forest Member was named for the PEFO area, the type section is near Zion National Park in southern Utah (Gregory, 1950). Throughout much of the outcrop belt, the Petrified Forest Member does not posses lithologies similar to the "lower" part (Blakey and Gubitosa, 1983; Dubiel, 1991, 1992, 1994; see above). Exclusive of northern Arizona, the southern Monument Valley area of Utah and westernmost New Mexico, the Sonsela Member and its probable equivalents lie directly on equivalents of Gregory's (1917) original division D (i.e., Monitor Butte and Bluewater Creek Members) or cut through them (e.g., Stewart et al., 1972b; Repenning et al., 1969; Lucas et al., 1997). Thus the type section of the Petrified Forest Member would include only the "upper" part of the member, in accordance with its use here. In fact, the absence of the "lower" Petrified Forest Member between the Monitor Butte and Bluewater Creek (=lower red) Members and the Moss Back Member (a probable equivalent of the Sonsela) was used as supportive evidence for the use of the term Monitor Butte Member up to the base of Sonsela Member within PEFO (Dubiel et al., 1999); also negating the differentiation of "lower" and "upper" portions of the Petrified Forest Member.

At this time it is unclear as to the detailed correlations between the Petrified Forest Member and other members in the area separating the type section and PEFO. Until these correlations can be verified it is the author's opinion that the Petrified Forest Member should be restricted to the interval between the Sonsela Member and the first laterally persistent limestone that marks the base of the Owl Rock Member at PEFO. This restriction would eliminate the original terms "lower" and "upper" Petrified Forest Member, and maintain utility and distinction between the differing lithologies of the Blue Mesa and Petrified Forest Members as used in this study. This approach also alleviates the problems of inclusion produced by raising the rank of the Sonsela to a member.

As here restricted the Petrified Forest Member in the vicinity of PEFO is an interval of deep red and purple mudstone and subordinate, laterally-continuous sandstone with only locally significant proportions of extrabasinal clasts. Facies assemblage H is assigned to the Petrified Forest Member (restricted). The lower contact with the underlying Sonsela Member is broadly gradational. The Petrified Forest Member in the PEFO area, as restricted, can be distinguished from the Blue Mesa Member by its predominantly red coloration, moderately- to well-lithified sheet sandstone bodies with high degrees of lateral continuity, general greater lateral continuity of units, and dominance of vertic features (cf., Driese and Foreman, 1992) in the paleosols. The Petrified Forest Member can be distinguished from the Sonsela Member by its greater lateral continuity of units, predominance of red coloration, less abundant sandstone, dearth of ribbon sandstone bodies and heterolithic deposits, and smaller amounts of variability in mudstone units.

## CONCLUSIONS

This study supports the use of member rank for the Sonsela Member of the Chinle Formation. The Sonsela Member within PEFO was found to have a tripartite subdivision similar to that described for the type section (Akers et al., 1958) and recently within PEFO (Heckert and Lucas, 2002b). However, this study disagrees with Heckert and Lucas (2002b) regarding nomenclature of the upper bed, lateral correlations, and the propriety of formal vs. informal nomenclature. Informal nomenclature is preferred by the author due to difficulties in regional correlation, partially due to local absence of units and rapid lateral facies variations. In my opinion this approach maximizes tradition of usage and utility on a local level, but does not constrain regional stratigraphic studies with excessive or rigid nomenclature.

Within the Sonsela Member the basal sandstone-dominated interval is informally referred to as the Rainbow Forest beds, and in PEFO consists of at least two laterally persistent sandstone and conglomerate bodies and minor mudstone lenses. The medial unit is informally referred to as the Jim Camp Wash beds, and consists of near equal percentages of sandstone and mudstone with predominant cut-and-fill architecture. Sandstone is found as large ribbon (3-20 m thick), small ribbon (<3 m thick) and thin (<2 m thick) sheet sandstone bodies. Mudstone is highly variable in character and lateral persistence. Heterolithic deposits of intercalated mudstone and sandstone are abundant in the unit. The Jim Camp Wash beds locally grade into and interfinger with both the underlying Rainbow Forest beds and overlying Flattops One bed. The upper sandstone-dominated unit is informally referred to as Flattops One bed, and consists of an interval of laterally persistent sandstone bodies with locally interbedded lenses of mudstone.

The Blue Mesa Member underlies the basal unconformity of the Sonsela Member. The term Blue Mesa Member is provisionally retained from Lucas (1993) based upon its distinctive lithology and distribution in northeast Arizona, westernmost New Mexico and the southern Monument Valley region of Utah. Further work on lithostratigraphic correlation between the Blue Mesa Member and type Monitor Butte and Petrified Forest Members needs to be completed to confirm the regional utility of the Blue Mesa Member.

The Petrified Forest Member as revised in this study is gradational with the underlying Sonsela Member. The Petrified Forest Member is restricted in the vicinity of PEFO to the red mudstone-dominated interval between the top of the Sonsela Member and the base of the Owl Rock Member. This restriction is warranted because of previous studies that have shown that regionally, including near the type area, the Petrified Forest Member does not contain lithologies similar to the underlying Blue Mesa and Sonsela members (Repenning et al., 1969; Stewart et al., 1972b; Blakey and Gubitosa, 1983; Dubiel, 1994; Lucas et al., 1997).

The proposed nomenclature is based upon lithologic unity as elucidated by the NASC (NACSN, 1983) and is consistent both lithologically and stratigraphically as demonstrated by mapping at a 1:24,000 scale of the southern portion of PEFO (Woody, 2003). The revised nomenclature in this study provides a robust and consistent framework to base future stratigraphic and sedimentological studies on, both locally and regionally. Future identification of the Sonsela Member should be made by comparison of local facies assemblages with those of the units above and below. Contrary to most previous studies that recognized the Sonsela Member as only large sandstone bodies (Billingsley et al., 1985; Deacon, 1990), the Jim Camp Wash beds may be the most regionally recognizable subunit of the Sonsela Member, particularly where large sandstone and conglomerate bodies are either abundant or absent. A distinctive siliceous horizon also appears to be significant as a regional marker bed within the Jim Camp Wash beds, although it is locally removed by the cut-and-fill architecture that is so prevalent in the unit.

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APPENDIX A – Description of measured sections. All UTM locations given using NAD 27 CONUS datum.

### Section Agate Mesa West 1

Base of section, UTM Zone 12S, E607822, N3860933, at top of Rainbow Forest beds.

| **Total thickness (m)** | **Unit-lithology. Upper contact.** |
|---|---|
| **Chinle Formation,** | |
| **Sonsela Member,** | |
| **Rainbow Forest beds:** | |
| .1+ | AA-light purple (weathered) medium-grained sandstone; fresh surfaces are moderate purple with small, pale gray, spherical mottles; slightly friable; contains local pebble sized chert clasts (predominantly yellow to brown, but some black and orange) — only exposed in wash so thickness is not known, or variations, but a subtle change in gradient of the wash indicates that is most likely a laterally persistent unit. Covered. |
| 9.3 | AB-covered |
| **Jim Camp Wash beds:** | |
| 10.38 | A-gray-green mudstone containing local large mottles of deep maroon mudstone; weathers to very pale gray; small (<1 mm) rhizoliths are common; red portions contain very weakly developed slickensides and are slightly coarser grained. Gradational. |
| 11.65 | B-deep, dusky-purple mudstone containing small (~1 X 0.8 mm) ped structures with a slightly redder coloration, decreasing up section; fissility increases as grain size decreases up section; rhizoliths are somewhat common locally, often in association with gray-green mottles; upper surface looks very similar to lower surface. Sharply gradational. |
| 12.93 | C-gray, nearly pure claystone with dusky red mottles; silt sized mica flakes are concentrated near the middle of the unit where the mottles are larger and purple coloration is also present in addition to the red; unit grossly resembles A. Gradational. |
| 17.43 | D-unit is almost identical to unit B; but because it is thicker these lithologic variations were seen — increase in mottling, and addition of purple colored mottles at 2.2 m for 0.4 m then decreases; the upper portion contains large pale gray mottles surrounding rhizoliths in a pure claystone with complex "net-like" mottling of deep dusky purple and ~30% greenish gray mottles surrounding black material or purely randomly; very poorly developed ped structures and moderately developed slickensides are seen in this upper portion; and uppermost portion has yellow-brown mottles associated with a unidentified metallic mineral with a blue sheen. Sharply gradational. |
| 17.98 | E- Identical to unit C. Gradational. |
| 21.11 | F-moderate dusky red mudstone with thin lenses and layers of light gray to almost white muddy silt; weathers to moderate to pale dusky red slope; the muddy silt layers are more concentrated near the top where they are thicker and more persistent, with a deeper red and finer-grained claystone as the interlayers; 0.7 m from the top is a band (0-40 cm thick) of highly mottled purple mudstone, this unit thickens and becomes more prominent on the southern flank of the ridge and is sharply overlain by the upper unit described below; this purple mudstone is mottled with red, purple and light gray and minor amounts of yellow-gray; small (~0.5 mm) ped structures are common, and decrease along with the mottling down-section; mottling becomes predominantly reddish down-section as the grey mottles disappear and the purple becomes more subdued. Gradational. |
| 22.03 | G-light dusky purple to dusky blue mudstone to fine-grained sandstone; gray mottles increase up-section to around 0.7 m where they are predominant in a slightly silty sand matrix, mottles in this section are dull red and purple with finer grain size; mottles decrease upward into a gray-green layer of silty very fine-grained sand. Sharp. |
| 22.75 | H-deep dusky purple mudstone; nearly identical to unit B. Broadly gradational. |
| 24.38 | I-dusky red mudstone with large amounts of gray-green mottles; mottles are often but not unanimously in bands forming slightly lighter-colored lenses on the slope; these bands are slightly coarser (muddy siltstone). Broadly gradational. |
| 26.13 | J-nearly identical to I, but with lenses of dusky red mudstone with almost no mottling 0.3-0.5 m thick and 2-4 m wide; becomes gray-green in upper 0.5 m with increased mottling; small (<1 mm) silicified rhizoliths are common in the red lenses and bands increasing in size at the upper portion; break in section. Gradational. |
| 27.61 | K-variable colored mudstone; grades from red with green mottles to deep purple with red and green-gray mottles to purple with lots of green-gray mottles associated with silicified rhizoliths (1-3 mm in diameter). Gradational. |
| 30.79 | L-moderate purple mudstone; gray-green mottles increase in size and abundance up-section to a point of approximately equal volumes to the purple mudstone then decrease rapidly; in this portion rhizoliths are rare, but do occur as nearly "hair-like" ribbons of silicified material; 1.2 m from the top, the mottles are <10% and directly associated with well-preserved rhizoliths around 1 mm in diameter; for 0.4 m mottles decrease and become spherical to slightly oblong in a moderate- to pale-dusky purple matrix with small ill-developed slickensides; the uppermost 10 cm is purple with increasing irregular, green-gray mottles to pure green-gray. Erosional. |

**Flattops One bed:** (Entire unit M has a highly variable thickness, several meters difference are observed in the adjacent buttes; predominantly due to variability in erosion on the top of the buttes.)

32.09 Ma-medium- to coarse-grained sandstone and conglomerate; slightly friable and pale gray, weathers to white; very poorly sorted; granules to pebbles of chert throughout, often defining cross-sets (very low angle trough), small amounts of volcanic clasts also seen locally, substantially larger (both median =5 cm and mode=6.5 cm averages) than the chert pebbles (<3 cm); conglomerate content and size increases upward. Erosional.

32.89 Mb-shallow scour of low angle cross-bedded conglomerate interbedded with clean sandstone; forms a small ledge. Sharp.

34.39 Mc-fine- to medium-grained, moderately sorted sandstone, coarse sand-sized chert grains are common in the coarser grained portions; locally small pebble chert clasts help define low-angle, tabular cross-bedding. Erosional.

35.89 Md-granule to pebble conglomerate; base is marked by pebble to small cobble sized, well-rounded to subrounded chert clasts, some small (<2 cm) volcanic clasts (<20% volume), and some very large (10-35 cm) deep red with some small gray-green mottles, fine-grained, well-cemented sandstone clast that are well-rounded; granules in the unit are well-rounded purple mudstone clasts and <10% chert granules; lower portion is horizontally laminated; medial portion is small-scale, moderate-angle, trough crossbedded dominated by granules, upper portion is moderate-scale and -angle tabular cross-bedded granule to pebble, with some small cobbles of purple mudstone, conglomerate; locally grading into moderately well sorted, medium-grained sandstone with large-scale, moderate-angle cross-sets defined by coarser grains and conglomerate sized clasts. Erosional.

39.29 Me-poorly sorted conglomerate with low-angle, large-scale tabular crossbedding and horizontal laminations; some laminations are well-sorted, coarse-grained sandstone only; sandstone laminations increase up-section to become nearly exclusive, but in medium- to coarse-size fractions, but with pebbles to small cobbles (predominantly of chert) and better-cemented, very coarse-grained sandstone helping to define some laminations.

Top of Flattops One bed (top of mesa)
Top of section, UTM Zone:12S, E607511, N3860954.

### Section Blue Mesa 1

Base of section, UTM Zone 12S, E614277, N3866793.

**Total thickness (m) Unit-lithology. Upper contact.**

**Chinle Formation,**
**Blue Mesa Member:**

.30 A-dusky blue, slightly silty claystone; some blocky to elongate, moderately-developed peds; some small (<1 mm) pale green mottles; very sparse, small (1 mm to 1cm) calcareous nodules; weathers to low rounded slopes covered by talus, mostly clasts. Covered.

1.4 B-covered. Covered

**Sonsela Member,**
**Rainbow Forest beds:**

6.53 C-gray sandstone; lower 3 m is medium- to fine-grained sandstone with broad lenses in the upper part of small pebble and granule chert clasts; base has some fragmentary fossil material; upper 2 m is fine-grained sandstone; grains in both are subangular to subrounded and predominantly quartz, but also include red chert fragments (unsure of feldspar %); sedimentary structures dominated by large-scale, low-angle trough cross-bedding where they are seen ( usually not visible); weathers to pinkish gray to very pale purple with a ledge and slope morphology. Sharp.

8.02 D-fining upward sequence; base is 5 cm of mudstone rip-up clast bearing medium-grained sandstone; grades upward to well-sorted, very fine-grained sandstone; fresh surfaces are very pale grayish-purple with pale gray-purple on weathered slopes; thin lenses of mudstone similar to the rip-up clasts are seen at the base. Sharp.

**Jim Camp Wash beds:**

9.03 E-pale greenish-gray claystone; minor amounts of slickensides present; grades upward into very pale dusky red, fissile shale with some irregular subspherical mottles; grades upward into pale dusky red, silty mudstone with moderate amounts of mottling; weathers to an irregular, moderately-steep slope of pinkish- and purplish-gray; topmost 4 cm is a small ledge of clay with abundant mottles and increased cementation, dusky red in color with weakly developed, small (<1 cm) ped structure; rhizoliths, up to 5 cm in diameter, are seen at the top and bottom of unit. Sharp.

9.51 F-pale dusky red, slightly sandy siltstone, very weakly laminated, lots of large green-gray, subspherical mottles; unit coarsens up by the addition of more sandy material; weathers to a moderate slope. Sharp.

9.86 G-dull red-brown mudstone with a fair amount of gray-green mottling, but with some dusky purple irregular mottles as well; small but fairly well-developed ped structures; very weak laminations, and maybe even ripple laminations are faintly seen locally; rhizoliths up to 8 cm long, 0.8 cm in diameter are common, as are fine rhizoliths (<1 mm) in hand sample; preservation is siliceous and some of the finer ones may be preserved as carbonaceous material. Abruptly gradational.

10.39 H-dull red, silty sandstone; weak, relict ripple lamination; large green-gray mottles grades up-section to slightly coarser silty sand with fine-grained sand sized mica grains becoming very common near the top. Sharp.

12.00 I-dusky purple claystone; well developed slickensides; some small subspherical to irregular green-gray mottles, sometimes following rhizoliths that are 1 mm to 1 cm in diameter, colors usually follow the larger ones; hand samples shows numerous "root hair" sized siliceous rhizoliths; some irregular mottles are slightly calcareous; upper portion has increasing mottles producing a lighter color on the weathered slope and more rhizoliths, but of the same size, "root hairs" however are not as common; weathers to a steep, irregular dusky red-purple slope with "blotches" of pale purple to gray from mottles. Gradational.

18.32 J-deep dusky purple claystone with moderate to large amounts of irregular mottling and small rhizoliths; grades laterally in 5 m to deep purple mudstone with large subspherical mottles and no rhizoliths; small (5 mm diameter, 2 cm long) possible burrows (meniscate); entire unit grades upward into dusky blue; weathers to moderate slope with irregular coloration, with less mottling from 1.5-3 m; at 4.5 m poorly-developed calcareous nodules are at the center of mottles, large, but sparsely distributed slickensides, and cm scale blocky to irregular peds(?); by 5 m no sign of the peds or slickensides was observed. Abruptly gradational.

18.93 K-pale green-gray, poorly-sorted, fine-grained sandstone; black grains nearing medium-grain size are common (~20%) along with mica gains (~15%), the rest of the grains seem to be fairly normal composition, Qtz, feldspar, etc.; weathers to very pale gray, steep slope. Broadly gradational.

19.22 L-light greenish-gray to light dusky purple mudstone; well-developed, small (~5 mm) peds, which are either greenish-gray or purple; the gray ones are siltier than the purple; weathers to a pale gray-purple steep slope. Abruptly gradational.

20.71 M-dusky purple mudstone; mottles decrease up section. Sharp.

21.62 N-very pale gray, slightly silty claystone. Broadly gradational.

23.98 O-dusky reddish-purple, moderately well-sorted, fine-gained sandstone; pale green-gray mottles in lowest 0.5 m; large (>1 cm) rhizoliths common in lower portion; small rhizoliths seen throughout; faint low-angle, small-scale planar cross-bedding; upper portion is well sorted. Sharp.

25.21 P-pale grayish green mudstone; becomes siltier up-section, where it also has a "network" pattern of pinkish red siliceous mottles; lenticular in nature, not seen off of the ridge (5 X 15 m); similar lenses are seen to the N but not to the S; weathers to moderately steep slope and local knob. Sharp.

26.26 Q-dull red-brown, poorly-sorted, matrix-supported conglomerate; clasts are dark yellow and brown chert; matrix is very muddy and silty; weathers to a low slope, and locally to a very thin ledge; locally the pebbles are in small-scale, high-angle, planar cross-sets. Covered.

29.84 R-dull grayish red-brown, poorly-sorted, fine- to medium-grained sandstone; contains deeper red, dusky red-purple and yellow mottling; yellow often surrounds carbonized plant fragments (up to 3cm in long dimension); grades upward into sandy mudstone with yellow to yellow-orange mottles sometimes surrounding more sand-rich areas. Sharp.

40.12 S-moderately well-sorted, medium-grained sandstone; color is various shades of gray on fresh surfaces; pinkish-gray to pale gray on weathered surfaces; rhizoliths preserved as siliceous and carboniferous material are moderately common in the basal portion; grades into sandy mudstone, largely sandy siltstone; subunit contains local, yellow-tan stripes in a vertical orientation; local lenses of sandy material are present, as are rare lenses of chert granule to small pebble clasts; overall unit fines upward to lenses of claystone, thick lens of 2 m present at top; weathers to steep, very pale gray slope; moderately well indurated on fresh surfaces. Erosional.

**Flattops One Bed:**

48.63 T- dark gray-brown, well-sorted, medium-grained sandstone; well indurated; local lenses of reddish- to brownish-gray, fine-grained sandstone lenses; color lightens upward on weathered surfaces from tan to yellow-gray to pale gray; high- to moderate-angle, moderate- to large-scale, planar and some trough crossbedding; small pebbles of chert often help define cross-sets; some crossbedding very high angle (>30°); sets are 0.5-2 m high; conglomerate is less prevalent to S of section and up-section; up-section also has more trough cross-bedding (large- to very large-scale, low angle); logs common near base of unit. Erosional, covered by Qd.

Top of Flattops One bed (top of mesa)
Top of section, UTM Zone 12S, E614134, N3866676.

### Section Camp Butte

Base of section, UTM Zone 12S, E612581, N3867223.

**Total thickness (m) Unit-lithology. Upper contact.**

**Chinle Formation,**
**Blue Mesa Member:**

4.92 A-blue-green-gray mudstone, nearly pure claystone; color varies slightly on weathering surfaces laterally to dusky blue; fresh surfaces are blue-green and blue-green-gray; a thin fine-grained, green sandstone lens (0-8 cm thick) occurs lateral to the section at 2 m, above the sandstone, but still in the lens, is greenish-gray claystone; measured unit becomes higher in clay content lateral to this scour for about the same thickness, even though the scour doesn't reach the actual section; weathers highly "bentonitic"; *in situ* stumps occur laterally in this unit. Gradational.

8.63 B-dusky blue-purple, slightly silty mudstone; weathered surfaces show diffuse areas of pale dusky blue; fresh surfaces are blue-gray with diffuse mottles of dusky purple; 1-5 mm diameter, weakly developed peds (?) were seen; red nodules covered many surfaces, but were only seen as very diffuse in fresh surfaces, locally they formed thin layers of coalesced, mm-scale nodules on the surface; mottles of dusky blue become dominant at 1-2 m and then decrease above; surface is heavily weathered in most places.

Very broadly gradational; taken as when purple is vastly more common than dusky blue.

16.07 C- deep purple mudstone; bentonite type weathering forming a steep slope; at 0.7 m is a fine-grained, poorly-sorted, gray-purple sandstone (15 cm thick) filling a local, broad scour (traceable for up to 40 m); mottles abruptly decrease above this layer, even where scour isn't present, and are represented as small (<1 cm) spherical mottles with local irregular mottles vs. the large irregular ones noted below and in B; fresh surfaces in this section are deep purple with diffuse areas of reddish purple and dusky blue; mm-scale, very ill-defined ped structures (?) are seen; small slickensides are common; another change is seen at 3-3.5 m where reddish purple mottles drastically increase; mottling overall decreases up-section; and slickensides are not seen above 3.5 m until 6 m; light dusky blue to blue-gray mottles increase drastically to point where there is no purple, just light dusky blue with green-gray mottles; silt content increases as well. Erosional.

**Sonsela Member,**
**Rainbow Forest beds:** (Unit D, variable sandstone; wood was not seen in place here, but is seen elsewhere; two large piles of wood fragments were seen on slopes immediately below implying that at least one large log (~1 m) came out of this unit; subunits Dc and Dd not measured precisely due to steepness of slope)

17.57 Da-base is orange-tan on weathered surfaces, dusky blue and yellow-gray, somewhat mottled on fresh; very poorly sorted; largest grains were medium-grained; fine grains were most abundant; bone fragments common in lowest portion; rhizolith fragments and some chert pebbles locally define low-angle, moderate-scale crossbedding; subunit coarsens upward and becomes better sorted, but muddy matrix is still common; weathers to steep slope. Sharp.

19.29 Db-layered medium-grained sandstone, interbedded with material identical to Da; weathers to pale gray to grayish brown ledge and slope; fresh is pale gray to bluish-gray; contact between layers is usually, but not ubiquitously gradational; ledges are moderately-sorted, fine- to medium- grained and become thinner up-section; moderate-angle, moderate- and small-scale, planar and some trough crossbedding, often defined by very pale gray mudstone clasts, locally mudstone rip-ups are up to 30 cm and do not clearly define sets. Gradational.

25.6 Dc- very similar to Da; weathers to extremely steep partially covered slope; details are limited. Sharp.

28.00 Dd-moderately well-sorted, medium-grained sandstone; low- to moderate-angle, tabular crossbedded; angle decreases to very low angle at top; topmost layers may be horizontally laminated; purple mudstone granule-sized (but could be well-rounded, small pebble sized) clasts define many of the cross-sets; weathers to a small cliff given abundance of large talus blocks that partially cover Dc; only seen on this one butte, but other subunits seen elsewhere. Erosional.

Top of Rainbow Forest beds (top of butte)

Top of section, UTM Zone 12S, E612626, N3867120.

### Section Crystal Forest

Base of section, UTM Zone 12S, E610591, N3859345.

**Total thickness (m) Unit-lithology. Upper contact.**

**Chinle Formation,**
**Blue Mesa Member?:**

3.00 A-purple claystone; lots of gray-green mottling; some local areas of weak calcareousness in the center of some of the larger (~1 cm) irregularly mottled areas. Covered.

**Sonsela Member?**
**Rainbow Forest beds?:**

8.33 B-covered; logs weathering out in situ throughout interval. Covered.

10.95 C- fine-grained, well-sorted (in sand sized fraction, but with clayey matrix), gray-green sandstone; weathers green-gray in steep slopes. Sharp.

**Jim Camp Wash beds:**

17.16 D-green-gray mudstone; base has 3 layers, decreasing in thickness up section of purple mudstone and silty sandstone with greenish-gray mottles of sandstone; after last purple layer unit grades up into silty mudstone; grades laterally into very fine-grained sandstone with thin (1-5 cm), dull red, silty mudstone lenses; units are deeply weathered with bentonite-type weathering. Sharp.

19.91 E-interbedded mudstone and thin sandstone lenses; sandstones are silty and green-gray to pale reddish-gray, mudstone layers are predominantly dull red to dull red-brown with some green-gray; weathers to pale reddish-gray to moderate dull red; mudstone is generally slightly sandy, but is locally fissile and slightly silty; mottles are very limited in extent. Sharp.

21.69 F-purplish red mudstone overlain by pale dusky purple mudstone with pale gray mottles; lower subunit is 2-15 cm thick; rhizoliths occur throughout, but are especially common at 0.5 m where there is a drastic increase in mottling and rhizoliths on the N side of the outcrop, on the S side the layer is greenish-gray, after 1 m the subunit grades back into pale purple, similar to below; break in section. Gradational.

28.79 G-gray, sandy mudstone interfingering with purple mudstone; in the upper portion the purple forms thin stringers; rhizoliths are sparse but not rare; grades upward into silty mudstone and dark to moderate green to greenish-yellow in lenses; weathers to moderate slope. Erosional.

30.11 H-shallow lens of dark green-gray, fine-grained, poorly- sorted sandstone; slight upward coarsening trend; lens can be traced for 25 m N and 40 m S; wood is common laterally; local chert and some volcanics and quartzite pebbles to cobbles. Sharp.

30.57 I-fine-grained, poorly-sorted sandstone; upper portion contains numerous pebbles with a fine-grained sandy matrix; logs common laterally; break in section. Sharp.

40.73 J-partially covered sequence of lenses.

Ja-moderate green, sandy mudstone; lenticular in nature with internal lenses of lighter green (fine-grained sandstone) and dark greenish-gray mudstone. Sharp.

Jb-more covered than Ja; pale gray-green, fine-grained, poorly-sorted sandstone grading upward into poorly- to moderately-sorted, medium-grained sandstone with sparse small chert pebbles. sharp; taken as first laterally persistent and densely populated pebble conglomerate.

**Flattops One bed:**

51.44 K-fine- to medium-grained, gray to pale yellow-gray sandstone; most is well sorted; weathers to yellow-tan to tan-brown; low- to moderate-angle, moderate- to very large-scale (>1 m) crossbedding, some small scale, especially up section; moderate amounts of tabular cross-beds also present; some soft-sediment deformation; largest cross-set is 2.3 m high and over 20 m long (epsilon cross-bedding?); small amounts of pebble conglomerate help define some high- to moderate-angle cross-sets; cross-sets form complex interaction with each other, often with widely varying directions between sets; slight cut-and-fill type geometries. Erosional, covered by Qd.

Top of Flattops One bed (top of mesa)

Top of section, UTM Zone 12S, E611669, N3858766.

### Section Dry Wash N

Base of section at contact with Blue Mesa Member, UTM Zone 12S, E610014, N3856388.

**Total thickness (m) Unit-lithology. Upper contact.**

**Chinle Formation,**
**Rainbow Forest beds:**

3.37 A-dull red-gray, very fine-grained sandstone; contains logs at this level on the other side of the wash; locally interbedded with mudstone, claystone and minor silty sandstone; silty sandstone is slightly paler than the rest, claystone is deep red-brown with sparse, very small, spherical mottles; weathers to fairly uniform moderate slope; color variations difficult to see on weathered surfaces; grades laterally into very pale gray, medium-grained sandstone. Sharp.

**Jim Camp Wash beds:**

4.16 B-very pale gray, fine-grained sandstone filling a local scour surface into dusky purple to slightly purple-gray mudstone with moderate amounts of yellowish green-gray mottles; weathers to steep slope with high degree of bentonite-type weathering. Abruptly gradational.

5.24 C-pale yellow- to greenish-gray claystone (similar in color but paler than the mottles in B); weathers to low slope with very well-developed, bentonite-type weathering. Covered.

12.58 D-moderate dull gray mudstone; some rhizoliths of yellowish material (carnotite?) throughout, but sparse in distribution; highly weathered surface forming an irregular, moderately steep slope covered with bentonite-type weathering; local broad lenses of silty and sandy material are present throughout the section. Sharp.

18.66 E-base is a 0-2 cm thick calcareously cemented, very fine-grained sandstone, locally ripple laminated; sharply overlain by light greenish-gray, silty sandstone; weathered surface has a slightly banded appearance with thin layers of darker and more greenish-gray, very pale to moderate pinkish-gray, and local and minor green; green layers locally weather into very small ledges; the rest is uniform forming a moderate slope; the greenish- and pinkish-gray layers are generally very fine- to fine-grained sandstone, but can be up to medium-grained; pale gray claystone layers are also present. Sharp.

21.08 F-moderate greenish-gray claystone; grades up into silty and sandy mudstone; some (very few) very small rhizoliths; a calcareous layer ~5 cm thick is present at 2.0 m; sandier layers are slightly darker; no other features were seen; weathers to moderate slope of pale greenish-gray. Gradational.

25.08 G- dull dusky purple mudstone with large, gray, irregular mottles; color darkens and mottles decrease upwards from base and then increase again as ~1 cm spherical mottles surrounding nodules. Erosional.

**Flattops One bed:** (Unit H is a yellow- to brownish-gray sandstone; scoured into by Quaternary sandstone to W and present erosional surface to E.)

25.38 Ia- yellow- to brownish-gray sandstone; base is dark brown weathered, gray on fresh surface, highly-indurated, calcareous pebble conglomerate. Sharp.

27.38 Ib- tan-gray, fine-grained sandstone; weathers to slope, slightly darker in color; moderately well sorted. Erosional.

29.88 Ic-moderate to dark tan, medium-grained sandstone; fresh surfaces are gray; well-sorted, dominated by very low-angle, large-scale, trough crossbedding, horizontal laminations are also common, but the extremely low angle of the crossbedding makes some determination slightly difficult. Gradational.

37.58 Id-partial covered, fine- to medium-grained; generally well-sorted sandstone; local scour-and-fill is prominent between subunits; general trend is to fine upward, although the largest grains are near the top; calcareous pebble and minor granule conglomerate is common in lenses; moderate- to large-scale, low- to moderate-angle, trough and some planar crossbedding is common; weathers to slope and ledge with subspherical, more indurated “concretions” occuring in the coarse end of medium-grained, well-sorted sandstone at the top, commonly separating along low-angle cross-sets into “disks”. Erosional.

Top of Flattops One bed (top of butte)

Top of section, UTM Zone 12S, E609792, N3856275.

### Section Lots Wife

Base of section, UTM Zone 12S, E610276, N3862740.

**Total thickness (m) Unit-lithology. Upper contact.**

**Chinle Formation,**
**Blue Mesa Member:**

0.50 A-dull purple mudstone; weakly-defined laminations of pale purple to grayish-green; mottles are abundant; some small <1 cm irregular areas of darker purple and grayish nodules, unit is not calcareous outside of the nodules. Abrupt.

0.95 B-pale greenish-gray, massive siltstone; some surfaces weather to pinkish-gray and have pinkish-gray mottling of mudstone areas (poorly developed peds?); some darker radiating blocky structures (<1 mm) as well as some fine-grained sandstone grains (~10-15%), especially in the top portions. Erosional.

**Sonsela Member,**
**Rainbow Forest beds:**

8.37 C-poorly-sorted, medium- to coarse-grained, pale purple-gray sandstone; locally is mottled with dark dusky purple mottles up to ~1 cm; has local small pebbles and granules of dark colored chert defining low-angle cross-sets; some thin, pure conglomerate units are seen infrequently, but can be up to 0.8 m thick; most pebbles are nearly purely intraformational (60-80%), some chert and locally volcanic clasts are also abundant; fines upward into sets; becomes well-indurated at top; low-angle, moderate- to small-scale, trough crossbedding and some planar crossbeds; unit grades into sandstone and interbedded sandstone and siltstone interval at top. Sharp.

**Jim Camp Wash beds:**

18.37+ D- purple to purple-red mudstone and silty sandstone interval; sand and silt is only in thin (<20 cm) lenses that are pinkish- to pale reddish-gray; mudstone units have only moderate amounts of slickensides at best, and are generally mottled with small, rounded, greenish-gray mottles; some calcareous nodule formation, but not many; the amount of sand and silt layers increases up section and the two thickest lenses are within 0.5 m of each other at the top of this measured portion; mottling increases up-section to point of light colored sand and silt layers and above have few mottles; these form fining up sequences. Top of section not measured.

Jim Camp Wash beds (incomplete section); sandstone interval above section partially destroyed by erosion in April 2005.

### Section Mountain Lion Mesa 1

Base of section at contact with Rainbow Forest beds, UTM Zone 12S, E608482, N3857866.

**Total thickness (m)** **Unit-lithology. Upper contact.**

**Chinle Formation,**
**Sonsela Member,**
**Jim Camp Wash beds:**

7.3 A-mostly covered pale dusky purple to dusky purple mudstone; slight mottling between the two colors, with minor amount of very pale blue mottles. Sharp.

7.95 B-siliceous horizon (silcrete); predominantly deep red in color, massive to "stringy" chert; locally layered, moderate gray and deep red with minor amounts of purplish tints; near top is slightly layered with thin interbeds of dusky blue to gray mudstone; this unit rapidly thins away from this area and is only 10 cm ~25 m away, but maintains the 10 cm thickness in all direction for at least 100 m. Sharp.

16.59 C-light dusky purple to dusky blue mudstone; variegated with small mottles of pale dusky blue in purple or dusky red to purple in bluish portions; small lenses of fine-grained sandstone are rare; contacts between the blue and purple portions are large-scale undulatory surfaces and contain mottles of the other color making the boundary diffuse. Covered.

17.79 D-mostly covered; moderate dusky red sandstone and sandy siltstone; is exposed better to N where it contains layers of moderate gray, fine-grained sandstone forming poorly-developed "hoodoo" layers and is capped by dusky red and gray interbeds dipping with low angles to the WSW; not seen to south; section is near southern limit of the unit; this unit taken as a whole appears to have an erosional contact with the underlying unit. Gradational.

21.09 E- pale dusky blue and moderate purplish-red mudstone and siltstone. Erosional.

24.89 F-very poorly-sorted conglomerate, predominantly well-rounded, black and white chert clasts; moderate amounts of red, yellow and orange; the white and black average small cobble size whereas the other colors average medium pebble size; matrix is gray silty sand; a thin local layer of the silty sand separated two beds of conglomerate here, but is thicker in other portions of the slope; no sedimentary structures were seen; to south it is represented by a thinner layer of predominantly carbonate nodule clasts. Abrupt.

28.11 G- soft, moderate red and purple mudstone; grades to greenish-gray in upper 1.5 m. Erosional.

**Flattops One bed:**

36.03 H-light tan to tannish-gray to yellowish-gray sandstone; dominated by tabular crossbedding, local trough cross-sets are abundant; tabular sets are usually around 0.3 m deep and 2 m wide and are of moderate angle ~7-13Ú; troughs are considerably larger (up to 2 m high and several m wide) and are defined by crumbly weathering; local conglomerate lenses are prevalent especially near the top; nearly uniform up-section increase in conglomerate percentage; upper layers also contain a larger percentage of carbonate nodule to chert clasts.

Top of Flattops One bed (top of ledge)
Top of section, UTM Zone 12S, E608201, N3858495.

### Section Old 180 4

Base of section, UTM Zone 12S, E608325, N3850628.

**Total thickness (m)** **Unit-lithology. Upper contact.**

**Chinle Formation,**
**Sonsela Member,**
**Jim Camp Wash beds:**

1.84 A-generally well-sorted, medium-grained sandstone; color ranges from grayish-pink to pure gray on fresh surfaces; weathers gray-red to pale dusky red in a hoodoo type weathering pattern; contains 2 sets of large-scale, moderate- to high-angle, trough crossbedding; near the top of the unit is a 6 cm thick layer with large (up to 7 cm) clasts of deep red mudstone some with cracks filled with the surrounding sand (same as above and below); just below this some of the cross-sets are defined by thin sets of thin deep red mudstone. Sharp.

4.76 B-dusky red sandy siltstone with interlayers of weakly laminated silty sandstone only a few cm thick at 1.3, 1.8 and 2.1 m (sharp contacts at top and bottom, especially the bottom); the unit fines upward to dark, deep red mudstone with some green-gray mottling; silty sandstone layers are lighter in color due to increased sand content which is greenish-gray and increased green mottling; slickensides are observed throughout but are more developed above the last silty sandstone layer; the upper most portions contain well-developed blocky to slightly rounded ped structures. Sharp.

5.89 C-dull dusky red siltstone with minor amounts of dull gray-green mottling and some well-developed green elongate mottles around partially preserved very fine rhizoliths; mottling increases up-section and small ill-defined nodules begin to form; a well-developed nodule layer is at the top (nodules here are larger up to 4-6 cm, but still discontinuous in nature). Sharp.

6.94 D-deep red to purple mudstone; mottled with increasing greenish mottles up-section; becomes carbonaceous, but doesn’t develop truly defined nodules; gradational into siltstone with mudstone mottles; silt is greenish and slightly sandy, especially towards the top; mudstone is same color as below but slightly silty; 2 x5 cm nodules with lobate to discoidal morphology observed in the uppermost portion. Sharp.

6.99 E-well sorted, fine-grained sandstone; pale greenish-gray on fresh surfaces, weathers to dark brown; grains of quartz and some chert (slightly larger) and black accessories from hand sample; grades into a pebble conglomerate 15 m to north. Sharp.

8.37 F-poorly-indurated, moderately well-sorted, medium-grained sandstone; contains some pebble conglomerate laterally; unit laterally is either pure sandstone, pure conglomerate, or interlayers of both as well as maybe some siltstone and mudstone; color is generally yellowish green-gray to grayish-green, with conglomerate layers being dark brown due to the weathered carbonate nodule clasts. Gradational.

9.49 Ga-dark purple mudstone with green mottles often surrounding small clusters of sandstone as the units grade into one another in ~10 cm (shrink-swell features); small (generally <1 cm but up to 2 cm) round nodules become increasingly abundant up section as do well-developed slickensides; small areas of ill-defined rounded ped structures are locally seen in areas of the most developed nodules and slickensides. Gradational.

10.87 Gb-dark purple mudstone; the nodules of Ga begin to coalesce in elongate forms and greenish mottles increase throughout this interval being the most concentrated at the top. Gradational.

13.99 Gc- dark to dull dusky purple mudstone; lighter in color at top; decreasing mottles up-section; green-gray mottling sporadically throughout. Abrupt.

15.46 H-pale greenish-gray mudstone with small fibrous purple mottles in the lower portion; thin, partially solidified rhizoliths throughout, but without reduction halos; upper portion highly weathered- grades to sandy siltstone with abundant small (1-2 cm) nodules, very closely packed nodules and matrix are calcareous in the upper portions. Erosional.

**Flattops One bed:**

21.81 I-sandstone and conglomerate; base is a thin (~5 cm thick) pebble conglomerate; above this are various layers of sandstone and conglomerate; sandstone is well-sorted, medium- to fine-grained, yellowish-gray and poorly-indurated near the base, often forming a steep slope with small ledges of coarser, more indurated material; conglomerate layers increase upwards, many filling large scours (up to 2.5 m thick) with low-angle, trough cross-bedding; most clasts are carbonate nodules but some layers also contain chert, especially near the top; several segments of logs can be seen on the slopes, ranging from 8 cm to over 30 cm in diameter, mostly brownish in color, but with multiple shades of brown, orangish-red is the brightest color seen. Erosional.

Top of Flattops One bed (capped by Quaternary deposits on the mesa top).

Top of section, UTM Zone 12S, E608365, N3850851.

### Section Old 180 W

Base of section, UTM Zone 12S, E602742, N3853275.

**Total thickness (m) Unit-lithology. Upper contact.**

**Chinle Formation,**
**Blue Mesa Member:**

1.50 A-dark purple mudstone with dark green-gray, small, irregular mottles; weathers into a small “blowout” protected by log fragments and cobbles; weathered surface is dusky purple-gray. Sharp.

**Sonsela Member,**
**Rainbow Forest beds:**

8.31 B-largely covered; pale gray, moderately-sorted, medium- to fine-grained sandstone at base; purple mudstone with some mottling above; appears to be mostly sandstone with purple mudstone lenses. Covered.

15.23 C-very pale gray, well-sorted, fine-grained sandstone; weathers to steep slope with ledges at top and “hoodoos” on the uppermost slope to west of ledge and small cliff; weathered surfaces are pale gray to pale purple-gray to tan; grains seem similar to many other sandstone in area (quartz, feldspar, black accessories); at 4.5 m there is a ledge 0.3 m thick of non-indurated sand between two indurated ledges, the top surface of the bottom ledge has numerous rhizoliths in it and appears to be mottled to purple; in the interval between these two ledges there appears to be very heavily mottled and partially silicified mudstone, could be clasts (~30 cm) but weathering pattern did not allow a full determination, but suggests mudstone lens; rhizoliths were also common in the hoodoo forming area. Covered.

16.63 D-covered. Covered.

**Jim Camp Wash beds:**

17.24 E-purple-gray, poorly-sorted (lots of silty and muddy matrix material, but sand sized fraction well sorted), very fine-grained sandstone; weathers to red-gray, low slope; units F-N are not present laterally, E is the entire thickness. Gradational.

17.39 F-purple sandy mudstone; small, irregular, green-gray mottles; weathers to steep slope. Sharp.

17.54 G-dull red silty mudstone; very few mottles; some ~1 cm nodules; weathers to irregular slope. Gradational.

17.98 H-purple-gray, well-sorted, well-rounded, fine-grained sandstone; forms a lens; weathers to reddish-purple-gray moderate slope. Sharp.

18.20 I-deep red, very silty mudstone; forms a lens; weathers to an irregular red color on a moderate slope. Sharp.

18.91 J-fine-grained sandstone, very similar to unit H, but with clasts of mudstone that look like unit I. Sharp.

19.09 K-identical to I. Sharp.

20.41 L-identical to H. Sharp.

20.54 M-identical to I. Sharp.

21.44 N-fine-grained sandstone; identical to H, except for local rhizoliths near the base and that it fines upward to very fine-grained and is gradational with the overlying unit. Gradational.

22.85 O-moderate red, silty mudstone; weathers to steep slope and almost nodular looking rounded knobs on very steep slopes; small, sparse mottles with a fairly even distribution except for them being larger and more sparse at base; branching tubular-like structures (decapod burrows?) filled with material identical to P extend down from P in complex patterns with a concentrated distribution, deepest is to near the base but most are less than 0.5 m; found throughout the horizon, but complex branches are only seen in this immediate area. Sharp; possible original topography of ~.2 m is seen locally.

23.98 P-dusky blue mudstone; small ~1 cm rhizoliths are common near the base and are much less common in the upper portion, but thin rhizoliths do form "aprons" of "matted" material that extend down in "sheets" from the upper surface, nearly all the way to the base in several locations; these are often surrounded by green to yellow-green colors and are red in color themselves; mottles (pale gray, except those mentioned in association with the quasi-vertical "mats") are generally restricted to just around rhizoliths. Erosional; relief of 40-50 cm locally.

**Flattops One bed:**

34.38 Q- gray, moderately well- to well-sorted, medium-grained sandstone; weathers to dark tan to blue-gray steep slopes or small cliffs; large logs (up to 2 m in diameter) are observed weathering out of the unit, particularly near the top; low-angle, trough crossbedding of moderate- to large-scale are dominant sedimentary structures; but locally very low-angle, trough and moderate-angle, planar crossbedding, as well has horizontal laminations are important components; complex internal architecture (cut-and-fill); upper 3 m is predominantly conglomeratic and shows the largest scale features (mudstone clasts are very common in the lower portion of this upper 3 m, while chert clasts increase to slightly over 50% in the upper portion, mudstone clasts are also larger in the lower portion); general trend is to coarsen upward, although the largest grains never reach coarse grain size; mudstone clasts at top of unit are very pale gray rather than purple like those below; volcanic clasts (up to 20% of clasts in lenses) are usually slightly larger and more rounded than chert clasts (predominantly yellow and brown); most of the lenses only contain 3 varieties of volcanic clasts, but some contain all of the usual 5, plus at least one possible clast of granite (20-25 cm in diameter) and a possible meta-basalt clast (15 cm in diameter). Erosional, Qd.

Top of Flattops One bed (partially covered in Qd—lens can be traced as a level of splays and sandstones on N side of the road to ~7-10 m below main body of Flattops One bed; roughly equivalent to the first large, sheet-like lens below Flattops One bed on the mesa north of the Rainbow Forest).

Top of section, UTM Zone 12S, E602398, N3853272.