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REVISED UPPER TRIASSIC STRATIGRAPHY OF THE PETRIFIED FOREST NATIONAL PARK, ARIZONA, U.S.A.

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Abstract—During the last 40 years, a variety of informal names have been proposed for Upper Triassic stratigraphic units in the Petrified Forest National Park (PFNP) and vicinity. We both simplify and formalize this stratigraphy. All Triassic exposures in the PFNP pertain to various units of the Chinle Group. We identify localized, topographically low exposures of siliciclastic redbeds and purple mudstones as the Bluewater Creek Formation, the oldest unit exposed in the park. The oldest widely exposed strata in the park belong to the overlying Blue Mesa Member of the Petrified Forest Formation. Within the Blue Mesa Member, we recognize one formal, sandstone-dominated unit of bed-level rank, the Newspaper Rock Bed.

Sandstones and conglomerates of the Sonsela Member of the Petrified Forest Formation rest disconformably on Blue Mesa Member mudstones on an erosional surface (Tr-4 unconformity) that approximates the Carnian-Norian boundary. There is no separate "Rainbow Sandstone;" instead, beds previously assigned to this unit pertain to the basal Sonsela Member. The Sonsela Member is thus composed of three bed-level units in the park, units we designate as Rainbow Forest (basal sandstone and conglomerate), Jim Camp Wash (middle slope-forming, finer-grained interval) and Agate Bridge (upper sandstone and conglomerate) beds.

The Sonsela Member is conformably overlain by the Painted Desert Member. In the southern portion of the park, the Painted Desert Member includes three sandstone-dominated units we formalize as Flattops beds 2-4 (ascending). North of I-40, bed-level units cropping out in the Painted Desert include the Lithodendron Wash Bed (formalized here) and the Black Forest Bed. In the extreme northern portion of the park, pedogenic limestones of the Owl Rock Formation conformably overlie the Painted Desert Member. Locally, the Neogene Bidahochi Formation, including some interbedded lava flows, overlies the Painted Desert Member or the Owl Rock Formation. The youngest lithostratigraphic units exposed in the park are a variety of unconsolidated Quaternary colluvial, fluvial and eolian deposits.

Lithologic and tetrapod biostratigraphic evidence indicates that Chinle strata encompass a single significant unconformity at the base of the Sonsela Member, with strata below the Sonsela bearing tetrapod fossils of Adamanian (latest Carnian) age and the Sonsela and overlying units containing Revueltian (early-mid-Norian) tetrapod fossils.

Keywords: Petrified Forest, Upper Triassic, stratigraphy, Chinle Group, Arizona, Painted Desert, Sonsela

INTRODUCTION

The Petrified Forest National Park (PFNP) in east-central Arizona encompasses some of the most spectacular outcrops of the Upper Triassic Chinle Group in the American Southwest (Fig. 1). These badlands, combined with the extensive collections of fossil vertebrates from the park, enable us to construct a robust litho- and vertebrate biostratigraphy of Chinle Group units within the park, based on nearly 60 measured sections that integrate the majority of known vertebrate occurrences within the park. This can in turn be utilized to correlate Chinle Group strata across the Colorado Plateau. To this end, we formalize a variety of lithostratigraphic terms that have been used informally by previous workers. These terms include the Newspaper Rock, Rainbow Forest, Jim Camp Wash, and Agate Bridge beds, Flattops beds 2-4 and Lithodendron Wash Bed. Further, we follow Ash (1992) in recognizing the Black Forest Bed as a formal bed-level, stratigraphic unit. We assign all Triassic rocks in the park to the Chinle Group by a combination of litho- and biostratigraphy (Fig. 2). This combination yields a detailed, but not unwieldy, lithostratigraphy that future workers should find extremely useful in regional stratigraphic, sedimentologic, chronostratigraphic and paleoecological studies. Indeed, the succession of tetrapod fossils preserved in the park forms one of the most complete records of tetrapod evolution across the Carnian-Norian boundary.

The scientific understanding of the stratigraphy of the Petrified Forest has evolved from the preliminary observations of the original U.S. Army surveys in the latter half of the 19th century (see Ash, 1972a) through numerous workers to the synthesis we present here (Fig. 3). Science is not based on consensus, but on facts and testing hypotheses that attempt to explain these facts. Accordingly, our own understanding of the stratigraphy of the Park has grown, evolved, and even changed over the course of the decade each of us has studied Triassic strata in the park and beyond. What we present here are our current stratigraphic hypotheses and the mountain of data they aim to explain. To be certain, points of contention remain, and it is possible, even likely, that our own hypotheses will evolve still further and we may refute some of this work at a later date. However, it is striking that, in spite of the thousands of field days expended by diverse parties at PFNP, the only published stratigraphic frameworks specific to the park are little more than annotated overviews (Billingsley, 1985a; Ash, 1987a), or detailed, but not comprehensive treatments (Murry, 1990). This is unfortunate, as the actual body of work available for such synthetic studies is enormous and includes diverse papers, theses, dissertations, maps, and other

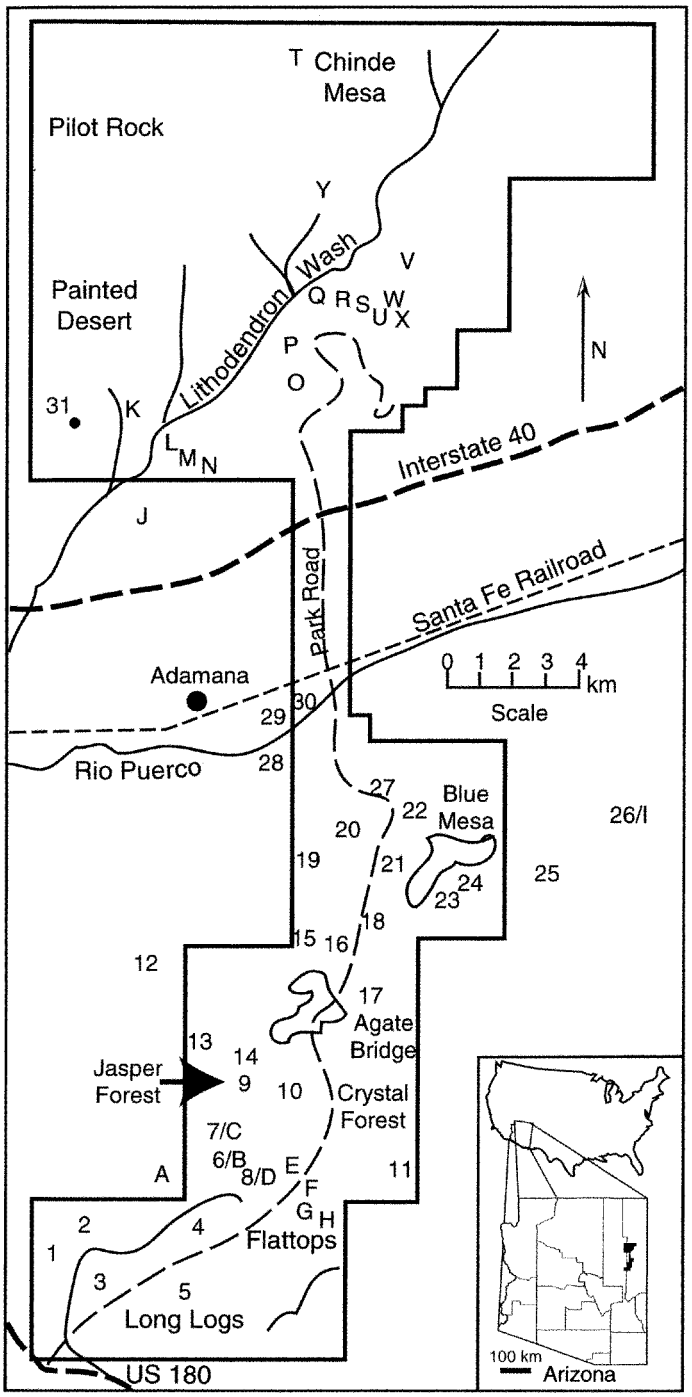

FIGURE 1. Base map of Petrified Forest National Park showing the location of measured sections utilized in this paper. Numbers indicate predominantly Blue Mesa Member-Sonsela Member sections, letters indicate predominantly Painted Desert Member sections.

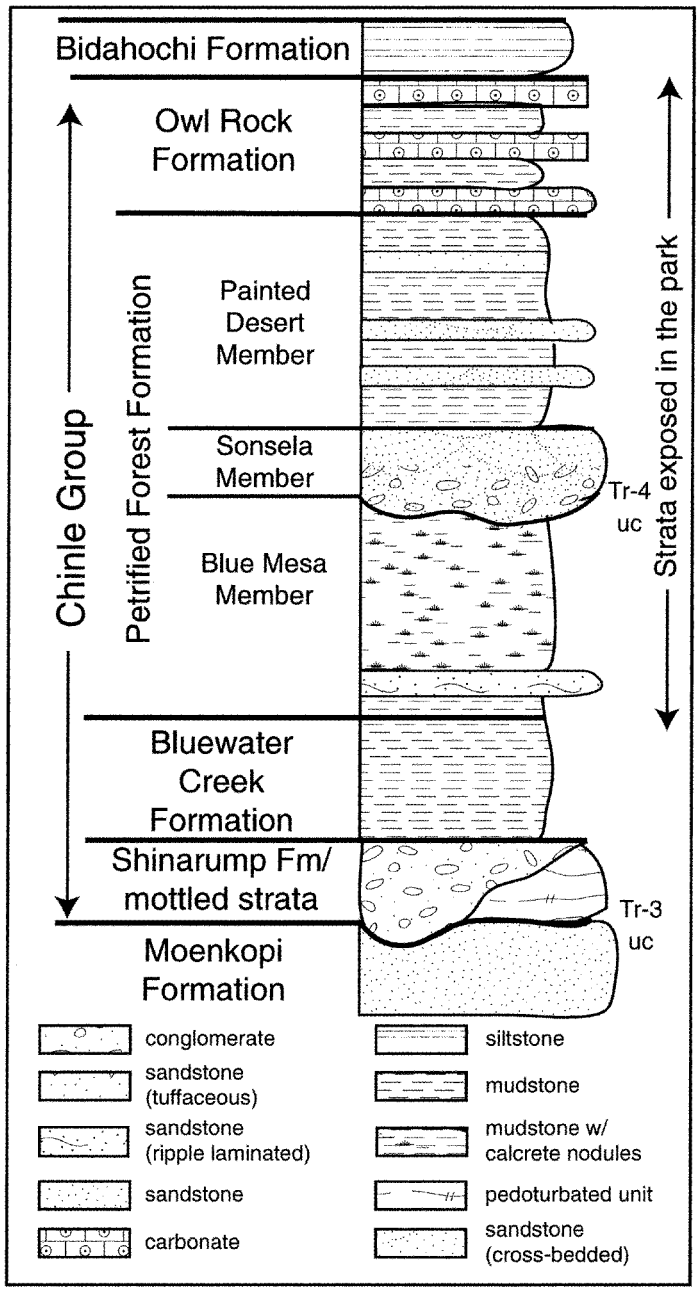

FIGURE 2. Generalized Upper Triassic stratigraphy of the Petrified Forest National Park and vicinity, northern Arizona. Total thickness of Triassic strata exposed in the park is approximately 275-300 m.

scientific contributions. What we present here is, we believe, the only paper that strives to incorporate all of this work and, among other things, conforms to the conventions of the North American Stratigraphic Code (NASC).

Mappability

The NASC (North American Stratigraphic Code) specifies that any named stratigraphic unit should be mappable at the 1:24,000 scale. We note here that Billingsley (1985b) mapped every single stratigraphic unit we describe here at the 1:50,000 scale. Although Billingsley's (1985b) map has some apparent drafting errors and other places where we disagree with his interpretations, it remains the only reasonably accurate, comprehensive geologic map of the park. Accordingly, we attempt to key every stratigraphic unit we formalize to Billingsley's (1985b) map, amply demonstrating the mappability of each unit and facilitating comparison of our observations with those of past workers in addition to providing a framework for future research.

Institutional Abbreviations

In this paper, we use the following abbreviations: PFNP = Petrified Forest National Park, Arizona (PEFO is also an acronym used within the National Park Service to identify Petrified Forest National Park); UCMP = University of California Museum of Paleontology, Berkeley.

PREVIOUS STUDIES

The stratigraphic nomenclature applied to Upper Triassic strata exposed in the PFNP began its evolution (Figs. 2-3) with the work of Gregory (1917), who assigned Upper Triassic strata in northeastern Arizona to the Chinle Formation, subdividing the unit into four informal divisions, A-D (in descending order; Fig. 3). These units were named much later as the Rock Point (Harshbarger et al., 1957), Owl Rock (Kiersch, 1956), Petrified Forest (Gregory and Williams, 1947), and "lower red," Mesa Redondo, and/or Bluewater Creek members (Akers et al., 1958; Cooley, 1958; Lucas and Hayden, 1989). Of these, intervals B-D are present in the PFNP, with the vast majority of the outcrops consisting of division C, the Petrified Forest Member (Gregory, 1950; Stewart et al., 1972a,b; Breed, 1972). Shortly after Gregory's time, Camp (1930, fig. 1) provided six generalized stratigraphic sections from the park and vicinity, and used these sections to order stratigraphically the Triassic fossils he and others had collected for the UCMP, but he made no attempt to alter the existing stratigraphic nomenclature.

Although numerous other workers would pass through the area and develop extensive paleontologic collections, the lithostratigraphic nomenclature of Triassic strata in the PFNP remained essentially unchanged until Cooley (1957, 1959) proposed a variety of informal stratigraphic terms, including the Newspaper and Rainbow Forest sandstones. Cooley (1957, 1958) also named the Mesa Redondo Member of the Chinle as a series of sandstones and conglomerates with minor mudstone stratigraphically above the Shinarump Formation and homotaxial with the "lower red member" near St. Johns, Arizona. He also assigned locally exposed badlands within the PFNP to the "lower red member" (Cooley, 1957), an observation that was not followed by later workers (Fig. 3). Akers et al. (1958) introduced the term Sonsela Sandstone Bed and correlated that unit from the type area in the Chuska Mountains to the southwest, into the PFNP.

Roadifer (1966) used much of Cooley's stratigraphy, although he introduced the confusing term "Camp Wash zone" for the stratigraphic interval above the basal Sonsela Member (Rainbow Sandstone of Cooley's usage), and named the Flattops sandstones above that interval, Flattops Sandstones 1-3 (Fig. 3). None of the informal units named by either Cooley or Roadifer were published, nor were type sections designated. However, much of this informal stratigraphy was followed by most later workers in the park (Fig. 3). Regional studies, such as Akers et al. (1958), Repenning et al. (1969) and Stewart et al. (1972a), utilized the same Chinle stratigraphy at the member level and above; the various bed-level stratigraphic units were not formally named by these workers.

Billingsley produced a summary article of PFNP stratigraphy (1985a) and a geologic map (1985b) of the park. The two are somewhat at odds with each other, especially in the upper portion of the section. Notably, Billingsley's (1985b) 1:50,000 geologic map included the following bed-level units in his interpretation of the lower Chinle: Rainbow Forest Sandstone, Newspaper Rock Sandstone, and "Brown" Sandstone. Billingsley (1985a) identified Roadifer's "Camp Wash zone" as Flattops Sandstone 1; consequently, he differed from previous workers in recognizing four Flattops sandstones in the southern PFNP, a conclusion followed by Espegren (1985) in an unpublished master's thesis on the sandstones in the southern PFNP. In the northern PFNP, Billingsley recognized two (1985b) to three (1985a) bed-level sandstone units in the upper Petrified Forest Member. However, Billingsley (1985a,b) followed the practice of previous workers and did not designate type sections for any of the units he described. Because no type sections were ever designated or described for these sandstones, all usage of these bed-level units continued to be informal, as in the summary article by Ash (1987a).

Ash (1987a,b), Murry and Long (1989) and Murry (1990) began to integrate paleontological collections into Billingsley's (1985a,b) stratigraphy. Long and Padian (1986), Murry and Long (1989) and Murry (1990) essentially followed Billingsley's stratigraphy but were the first since Camp (1930) to place some Upper Triassic fossil localities from the park into detailed measured sections. Deacon (1990) explored the Sonsela Member and its stratigraphic relationships in detail but did not introduce any new stratigraphic terminology. Farther to the east, Lucas and Hayden (1989) named the Bluewater Creek Formation for strata in west-central New Mexico that corresponded to the informal "lower red member" of Cooley (1957) and later workers.

Lucas (1993) elevated the Chinle Formation to group status, concomitantly raising the previous members to formation rank and beds to member rank. In the same work, Lucas designated and named type sections for two members of the Petrified Forest Formation in the PFNP, the Blue Mesa and the Painted Desert members, below and above the Sonsela Member, respectively (Lucas, 1993). This essentially settled the framework of stratigraphic nomenclature utilized here, although an interesting, nontraditional interpretation (Fig. 3) was proposed by Dubiel et al. (1995). Lucas (1994, 1995) also summarized how these changes affected lithostratigraphic nomenclature in the park. Lucas and Hunt (1993a) and Hunt and Lucas (1993a) subdivided the Chinle tetrapod faunas biochronologically into four land-vertebrate faunachrons (lvf). On the basis of these, Hunt and Lucas (1995) noted that strata in the PFNP contain Adamanian (latest Carnian) and Revueltian (early to mid-Norian) faunas, with the former found in the Blue Mesa Member below the Sonsela Member. We have previously followed this subdivision when correlating strata from the PFNP into adjacent regions (e.g., Lucas and Heckert, 1996; Heckert and Lucas, 1997) and in our own studies of the fossils and stratigraphy of the park (e.g., Heckert and Lucas, 1998a,b).

Since Lucas (1993) and Dubiel et al. (1995), both parties and their co-workers have published shorter articles on the stratigraphic problems within the park. Some use essentially the stratigraphy advocated and explicated here (e.g., Hunt et al., 1995, 1996; Heckert and Lucas, 1998a,b; Hunt, 1998; Hunt and Wright, 1999; Lucas, 2001), while others persist in using the older and, we believe, more ambiguous and cumbersome terminology (e.g., Dubiel et al., 1999; Herrick et al., 1999; Therrien et al., 1999; Therrien and Fastovsky, 2000; Ash and Creber, 2000; Ash, 2001; Jones et al., 2002). Demko (1995a,b) measured several detailed measured sections in the middle of the park, but made no systematic attempt to modify the stratigraphy proposed by Billingsley (1985a,b).

Long and Murry (1995) published a monograph on Late Triassic tetrapods, which includes extensive data from fossils collected from the PFNP. Their biochronologic conclusions regarding the fossils from the PFNP essentially follow previous workers, including Long and Padian (1986), Murry and Long (1989), and Lucas and Hunt (1993a) in dividing these collections into Carnian and Norian faunas, although there are notable differences between these authors regarding nomenclature and taxonomy of the specific fossils involved. Here, we modify and expand upon the lithostratigraphic work of Lucas (1993, 1994a, 1995) and formalize many of the stratigraphic terms proposed since the work of Cooley (1957).

STRATIGRAPHY

As defined by Lucas (1993), the Chinle Group encompasses all nonmarine Upper Triassic strata in the western United States, from Idaho to West Texas and from eastern Nevada to western

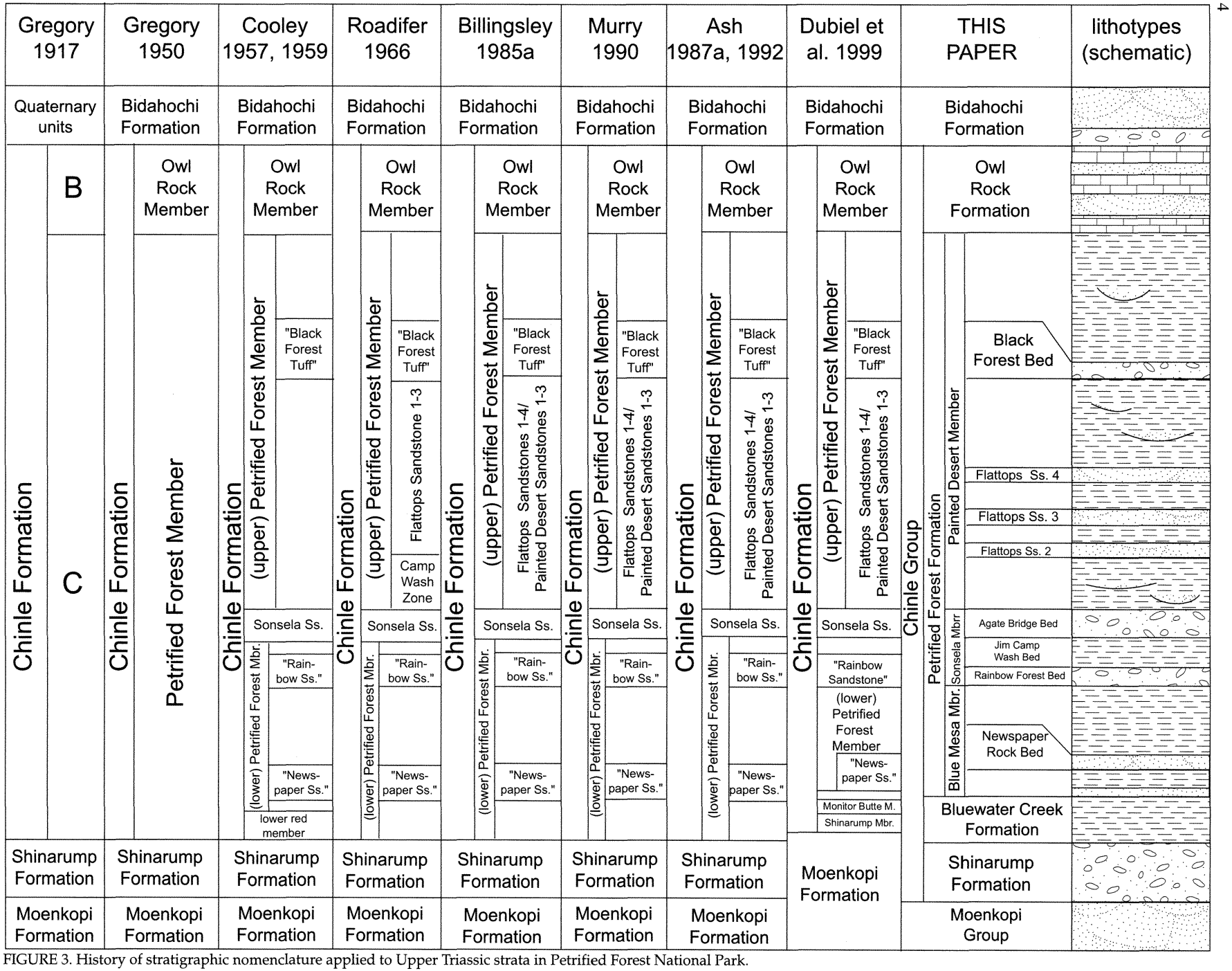

FIGURE 3. History of stratigraphic nomenclature applied to Upper Triassic strata in Petrified Forest National Park.

Oklahoma. These strata were deposited from late Carnian to Rhaetian time, approximately 230-202 Ma (Kent et al., 1995 timescale). Near Holbrook, Arizona, the Tr-3 unconformity of Pipiringos and O'Sullivan (1978) separates basal Chinle strata west of the park from the underlying Lower-Middle Triassic Moenkopi Group (Fig. 2). During the interval over which Chinle deposition occurred, regional events resulted in two intra-group disconformities, the Tr-4 and Tr-5 unconformities of Lucas (1993). Only the Tr-4 unconformity is present in the park. Regionally, this unconformity separates the Sonsela and its correlatives from underlying Chinle strata. Thus, within the park, the Tr-4 unconformity is recognized where deposits of Sonsela sandstones and conglomerates fill scours in and overlie mudstones and sandstones of the underlying Blue Mesa Member (Fig. 2).

In the PFNP, the following previously named Chinle units are exposed (ascending order): the Bluewater Creek Formation, the Blue Mesa, Sonsela, and Painted Desert members of the Petrified Forest Formation, and the Owl Rock Formation (Fig. 2). Inside the park boundaries the pedogenic limestones of the Owl Rock Formation are only exposed at the top of Chinde Mesa and vicinity (Fig. 1). The Painted Desert Member is widely exposed in the northern portion of the park and is the dominant unit observed from any of the overlooks there. The only widespread bed-level stratigraphic units in this area are the Lithodendron Wash and Black Forest beds (Figs. 2,3). The only exposures of the Painted Desert Member in the southern portion of the park are in the vicinity of the Flattops, at the western boundary of the park, and near the mesa informally known as "Martha's Butte." In these areas the Flattops beds 2-4 cap numerous mesas and buttes (Figs. 2,3). The Sonsela Member caps isolated mesa tops or crops out in "forests" of *in situ* logs throughout the southern half of the park and locally in the vicinity of Wildhorse Wash west of Lithodendron Wash. Blue Mesa Member strata crop out beneath the Sonsela and dominate the southern portion of the park and the low badlands in the vicinity of Wildhorse Wash in the northern part of the park.

Bluewater Creek Formation

Historically, most workers have agreed that the stratigraphically lowest exposures in the PFNP are low in the Blue Mesa (=lower Petrified Forest) Member (Fig. 3). Recently, some workers (Dubiel et al., 1995, 1999; Hasiotis and Dubiel, 1995) proposed that the oldest outcrops in PFNP pertain to the Moenkopi Formation, although their descriptions indicate that they actually mean "mottled strata," a name given to pedogenically modified strata at the base of the Chinle Group by Stewart et al. (1972a). This identification is at odds with the available stratigraphic and paleontologic data. We have refuted this anomalous correlation in detail elsewhere (Heckert and Lucas, 1998a), indicating instead that the stratigraphically lowest Chinle exposures in the park pertain instead to the Bluewater Creek Formation. Since (Figs. 3-4) that time one of us (ABH) has had the opportunity to examine the specific outcrops described as "Moenkopi Formation" by Dubiel et al. (1995). The following discussion is based upon those outcrops, which are in the NE1/4 of section 21, T18N, R24E.

From bottom to top, the following strata occur below the Blue Mesa Member in this area: (1) a coarse-grained quartzose, well-cemented sandstone that floors the wash; (2) waxy (bentonitic) reddish mudstones; (3) exceedingly thin (<15 cm thick) siliceous, color-mottled strata; and (4) additional bentonitic red-bed mudstones, the top of which show some indications of exposure and weathering before deposition of lithic wackes of the lower Blue Mesa Member. We identify these strata as typical deposits of the Bluewater Creek Formation. The Bluewater Creek Formation consists of interbedded mudstones, siltstones, and sandstones that constitute siliciclastic "red bed" deposits that are markedly different from the overlying Blue Mesa Member floodplain and paleosol deposits (Lucas and Hayden, 1989). Stratigraphically, the Bluewater Creek Formation is equivalent, at least in part, to Cooley's (1957, 1959) informal "lower red member" of the Chinle Formation (Akers et al., 1958; Repenning et al., 1969; Stewart et al., 1972a). At its type section, the Bluewater Creek Formation consists of 53 m of red beds, primarily interbedded red, reddish brown, and blue mudstones and red siltstones with some ripple laminated and trough crossbedded channel sandstones (Lucas and Hayden, 1989). Mudstones are generally less bentonitic than overlying Blue Mesa Member mudstones, with occasional horizons of calcrete nodules indicating limited soil development. Here we identify the Bluewater Creek Formation in the PFNP for the first time.

Near the bottom of our Newspaper Rock Bed type section (Fig. 4), at the base of the Blue Mesa Member, there is a 4.6 m thick bed of tuffaceous, highly micaceous, sandstone (equivalent to unit 2 of Lucas' type Blue Mesa Member type section). This sandstone/wacke interval is lithologically similar to the basal Blue Mesa Member in the vicinity of Fort Wingate, New Mexico, where approximately 5 m of ashy sandstone lie conformably on bentonitic mudstone "red beds" of the Bluewater Creek Formation (Lucas and Hayden, 1989; Heckert and Lucas, 1996; Lucas et al., 1997; Heckert and Lucas, 2002). In both cases, this sandstone is muddy and/or ashy, micaceous, and poorly sorted. Near Fort Wingate the basal Blue Mesa sandstones display more bedforms, particularly very low-angle trough crossbeds, but the bed in the Petrified Forest National Park exhibits similar features in the vicinity of the Teepees, where it is approximately 12.9 m below the Newspaper Rock Bed (Figs. 4B, 5). Therefore, we interpret this bed as representing the base of the Blue Mesa Member. The pale purple and grayish red-purple bentonitic mudstones below it therefore belong to a different stratigraphic unit, either the Mesa Redondo Formation of Cooley (1958, 1959) or the Bluewater Creek Formation (Lucas and Hayden, 1989). The presence of red (grayish red-purple and grayish red) mudstones below this sandstone suggests that this unit is the Bluewater Creek Formation, as the Mesa Redondo Formation is a much sandier unit (Cooley, 1958). These deposits thus most closely resemble the colors and lithologies of the Bluewater Creek Formation. Therefore, we continue to reject the conclusions of Dubiel et al. (1995, 1999), Hasiotis and Dubiel (1995), and Thierren et al. (1999).

Petrified Forest Formation

The Petrified Forest Formation overlies the Bluewater Creek Formation throughout the southern Colorado Plateau, including in the park, and is subdivided into the Blue Mesa, Sonsela and Painted Desert Members, in ascending order. Within the Petrified Forest Formation the only regionally unconformable contact is that of the Sonsela Member on the underlying Blue Mesa Member. As described above, the contact of the Blue Mesa Member on underlying strata is sharp but conformable. The Sonsela Member grades upward into the Painted Desert Member, which is conformably overlain by the Owl Rock Formation. Several sandstone-dominated units in the Petrified Forest Formation, particularly those in the Sonsela and Painted Desert members, are sufficiently extensive to merit bed-level rank. Each member and bed of the Petrified Forest Formation is considered separately in the following sections.

Blue Mesa Member

The Blue Mesa Member of the Petrified Forest Formation was defined by Lucas (1993) as 83+ m of bluish-gray to purple and white mudstones interbedded with several sandstone beds

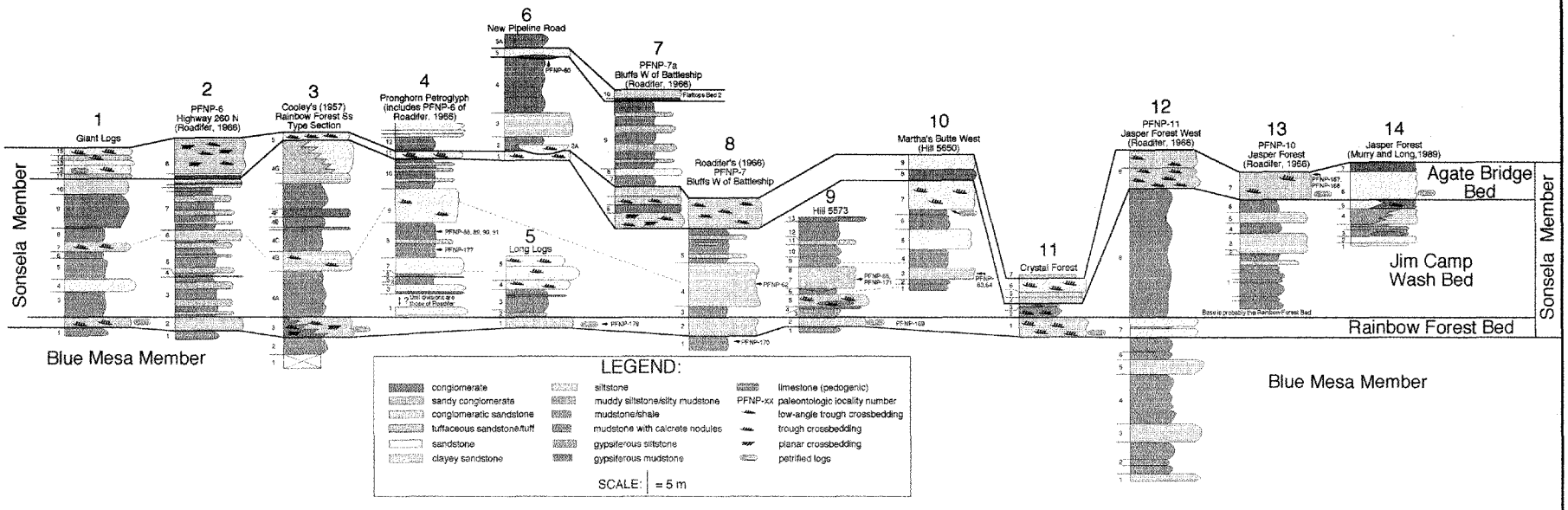

FIGURE 4A. Measured stratigraphic sections of the Blue Mesa and Sonsela members in the PFNP and vicinity.

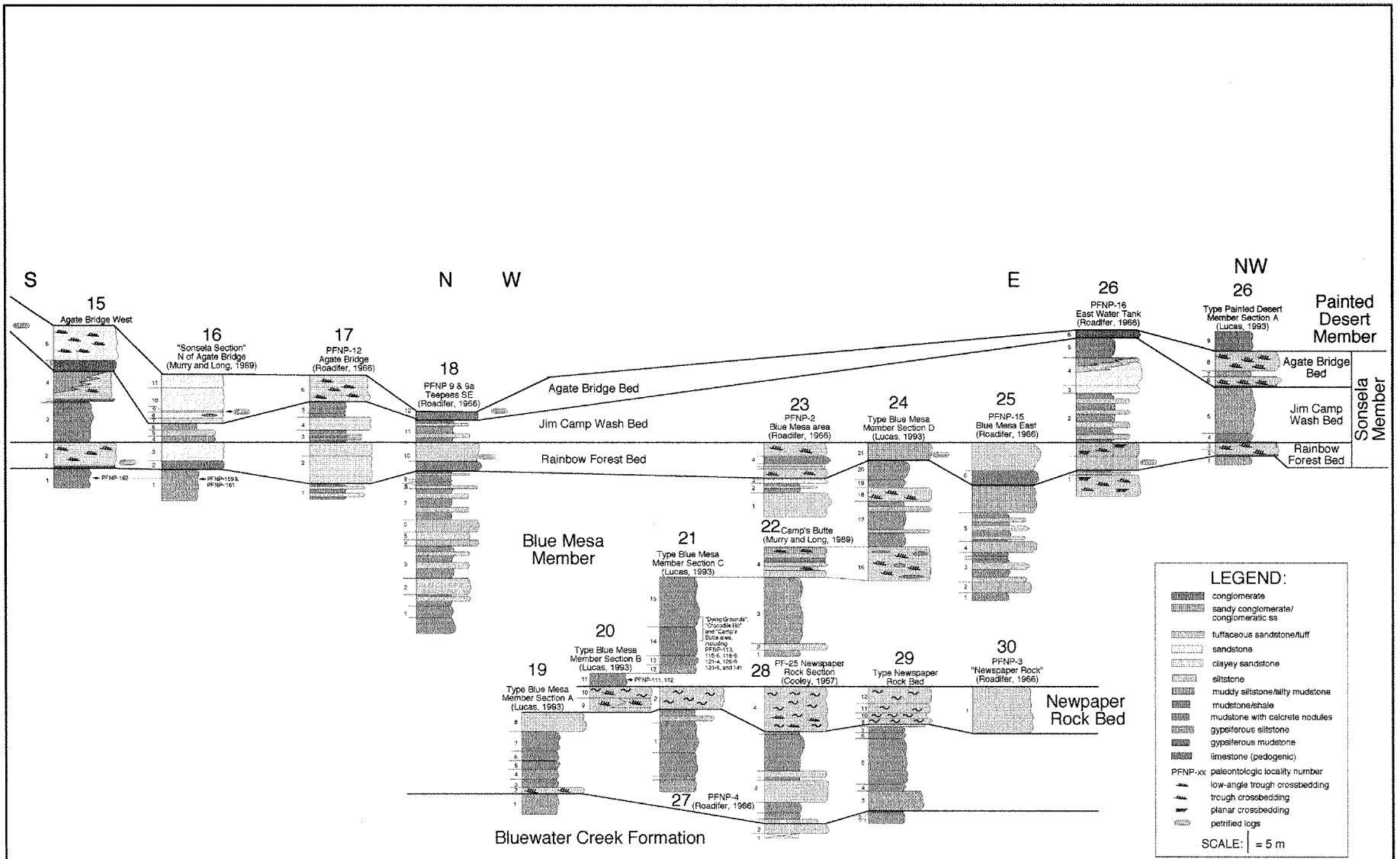

FIGURE 4B. Measured stratigraphic sections of the Blue Mesa and Sonsela members in the PFNP and vicinity.

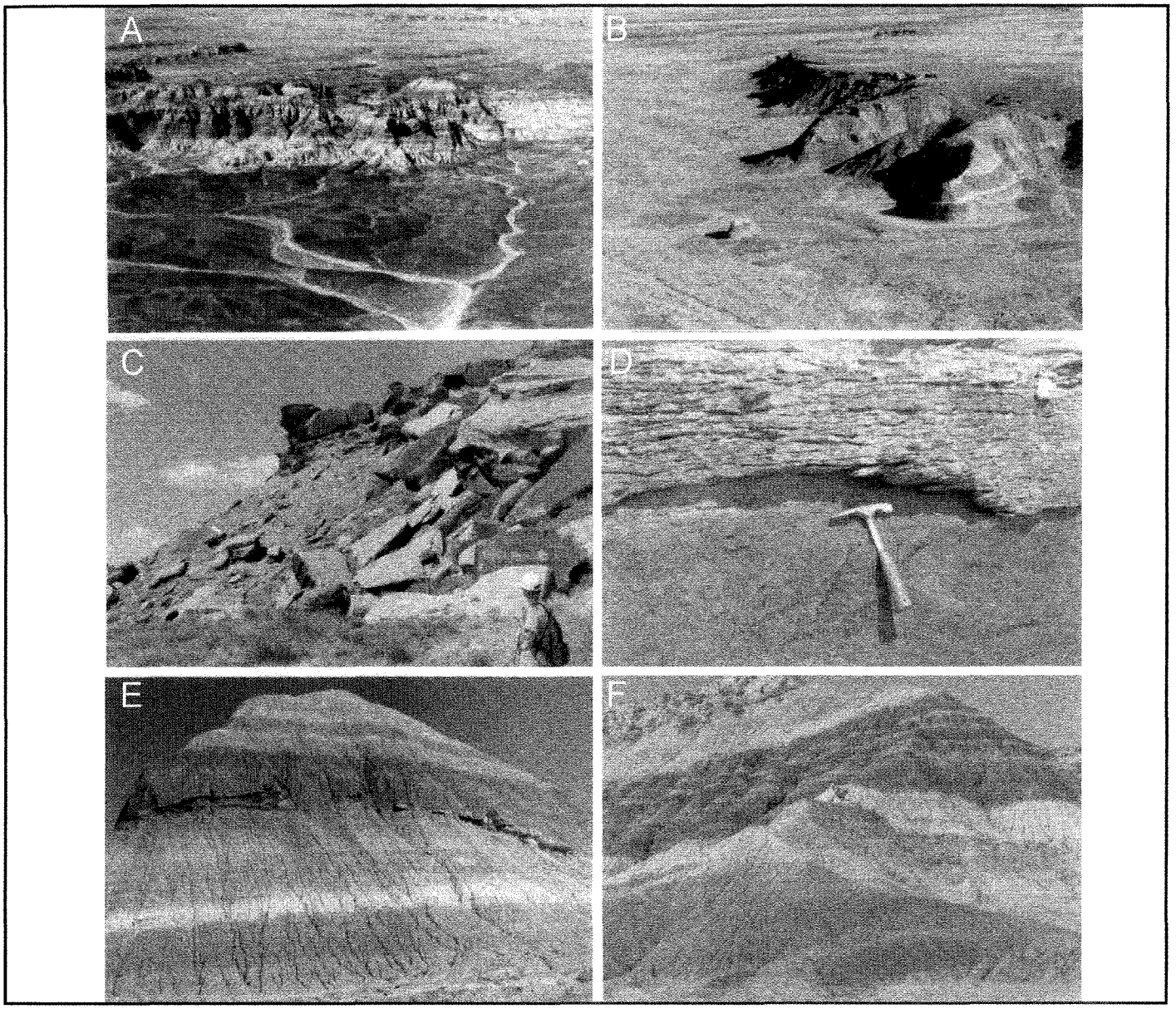

FIGURE 5. Photographs of Blue Mesa Member strata in the Petrified Forest National Park. **A**, Aerial photograph of Blue Mesa. **B**, Aerial photograph of the mesa held up by the Newspaper Rock Bed, view from the southwest. **C**, Overview of the type Newspaper Rock Bed immediately south of Newspaper Rock. **D**, Close-up of ripple-laminated sandstone in the upper Newspaper Rock Bed. **E**, Incised valley fill in the Blue Mesa Member at the Teepees. **F**, Uppermost Blue Mesa Member and lower Sonsela Member strata west of Agate Bridge.

of varying thickness and persistence (Figs. 4-5). Lucas (1993) measured the type section in four segments, from the Haystacks (units 1-8 in the SW1/4 SW1/4 SE1/4 sec. 21) through the Teepees (units 9-11 in the SW1/4 NW1/4 SW1/4 NE1/4 sec. 22; Fig. 5E) and "Camp's Butte" (units 12-15, SE1/4 NW1/4 SW1/4 sec. 23) to the Blue Mesa area proper (units 16-21 in the E1/2 SE1/4 SE1/4 SW1/4 sec. 23) in T18N, R24E in the PFNP (Figs. 4B, 5A). Because we have redefined the base of the Blue Mesa Member here, we now restrict that unit to the 77.7 m of strata above the basal redbeds (now assigned to the Bluewater Creek Formation) and below the basal conglomerate of the Sonsela Member.

Blue Mesa strata are typically grayish-purple and light greenish-gray bentonitic mudstones with lesser amounts of clayey sandstone and weakly indurated conglomerates. Locally, such as immediately above the Newspaper Rock Bed at the Teepees (SW1/4 SE1/4 NE1/4, sec. 22, T18N, R24E), there are minor red-bed mudstones (arroyo-fill facies of Kraus and Middleton, 1987). Color mottling, reduction spots, pedogenic bioturbation, calcrete nodules, and calcrete horizons are characteristic of Blue Mesa Member mudstones. These features document Triassic soil development, and it is widely accepted that the fine-grained facies of the Blue Mesa Member represent distal floodplain deposits and paleosols (Kraus and Middleton, 1987; Dubiel, 1989a,b; Hunt et al., 1995). Calcrete nodules are typically sideritic, and paleosols in the Blue Mesa Member probably indicate stage I to III calcrete paleosols (Bachman and Machette, 1977; Machette, 1986).

Blue Mesa Member sandstones are generally both compositionally and texturally immature. The sole exception is the Newspaper Rock Bed, described below. Otherwise, these sandstones are relatively muddy and/or tuffaceous, poorly sorted litharenites and lithic wackes. Micas, particularly biotites, are common. Cementation varies widely, but most often non-bed-rank sandstones are poorly indurated and weather to low, rounded slopes and blowouts, whereas well-indurated sandstone-dominated units

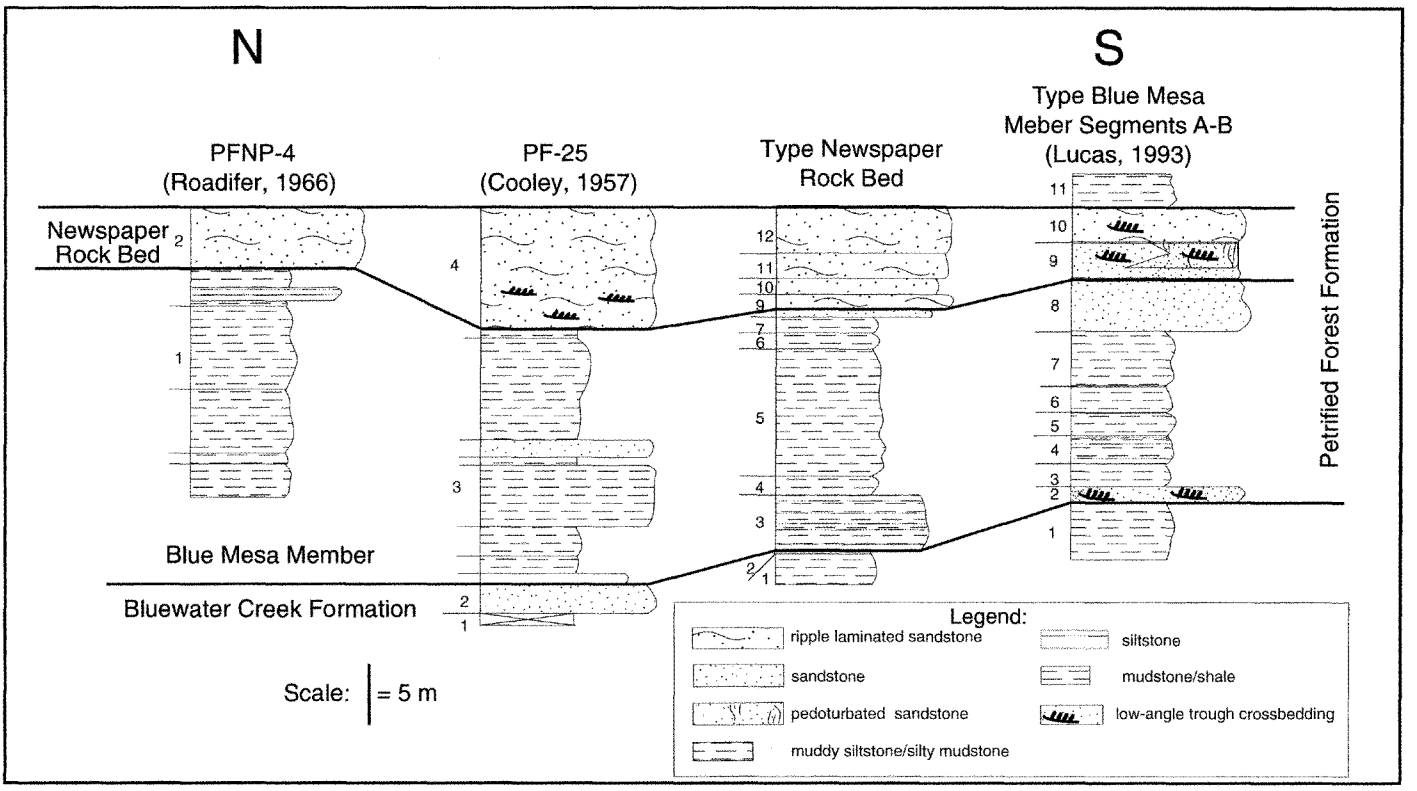

FIGURE 6. Type and nearby sections of the Newspaper Rock Bed.

tend to crop out as persistent low benches. Blue Mesa Member sandstones are commonly white, very light gray, light greenish-gray, yellowish-gray and bluish-gray. Most Blue Mesa Member sandstone deposits are thin (1-5 m thick) and lenticular and therefore difficult to trace laterally, but are often richly fossiliferous.

Newspaper Rock Bed

We designate units 9-12 of our Newspaper Rock Section in the SE1/4 SE1/4 NW1/4 sec. 6, T18N, R24E as the type section of the Newspaper Rock Bed (Figs. 5B-D, 6). Here the Newspaper Rock Bed is 8.7 m thick. The basal contact of the Newspaper Rock Bed is erosional, filling small scours on a series of light gray, grayish blue, and reddish purple bentonitic mudstones. Generally, the upper contact is missing, with discontinuous Quaternary deposits resting on a mostly stripped surface of the uppermost Newspaper Rock Bed, but to the south the Newspaper Rock bed grades upward into the middle Blue Mesa Member.

The Newspaper Rock Bed type section consists of moderately well-indurated, cliff-forming, ripple-laminated, very fine- to fine-grained, subangular to subrounded, micaceous quartz-arenites, 7.8-8.7 m thick (Fig. 6) that well represent Newspaper Rock Bed lithotypes, bedforms and thicknesses. Sandstones of the Newspaper Rock Bed are principally light greenish-gray to pale greenish-yellow and grayish-yellow green fresh, weathering to dark yellowish-brown (10YR4/2) on desert-varnished surfaces, some of which Native Americans utilized to create the petroglyphs from which the unit derives its name (Fig. 5C). These sandstones are typically ripple laminated and occur in superposed sets 1.2-3.1 m thick (Fig. 5D).

The Newspaper Rock Bed is a very localized feature, reinforcing the plateau just south of the Rio Puerco (secs. 9-10, 14-16 and 21-22, T18N R24E, Fig. 5B) before thinning and entering the subsurface in the vicinity of the Teepees farther south in the SW1/4 SE1/4 NE1/4 sec. 22, T18N R24E. Billingsley (1985a) mapped this unit as the "Newspaper Sandstone" (nss) in this area and outside of the park to the east, and we agree with his mapping in this area. We do not, however, think that strata he assigns to his "Newspaper Sandstone" in Lithodendron Wash in the northern portion of the park pertain to the Newspaper Rock Bed. These strata instead probably pertain to the younger Sonsela Member of the Petrified Forest Formation.

This unit has been identified informally for 45 years, usually as the "Newspaper Sandstone," (e.g., Cooley, 1957), and constitutes the only persistent, mappable, sandstone-dominated unit within the Blue Mesa Member. Because the Newspaper Rock Bed has been identified informally for so long there is a sizable database to work with in describing the unit. Sections measured by previous workers farther to the south (Cooley, 1957; Roadifer, 1966) indicate that the Newspaper Rock Bed locally reaches thicknesses of approximately 10-11 m in the vicinity of NW1/4 NE1/4 NE1/4 sec. 21, T18N, R24E (Figs. 4, 6). These deposits have been interpreted as representing channel fills of a meandering fluvial system (Demko, 1994, 1995a,b).

Sonsela Member

The PFNP lies near the western limit of the Sonsela lithosome as it is typically recognized (Stewart et al., 1972a), so beds traditionally identified as the Sonsela Member are often less than 10 m thick here (Deacon, 1990). However, we interpret the Sonsela differently, incorporating some strata previously assigned to the Painted Desert Member (upper Petrified Forest Member of previous usage), thus assigning as much as 40 m of strata to the Sonsela Member in the PFNP (Figs. 4,7,8). The lower contact is unconformable, with the Sonsela deposited on an incised topography developed on the Blue Mesa Member both within the PFNP (Billingsley, 1985a,b; Deacon, 1990) and throughout its outcrop area (Stewart et al., 1972a; Heckert and Lucas, 1996). Consequently, Sonsela Member thicknesses are highly variable throughout the park. The upper contact is gradational, with the Sonsela fining upward into the overlying Painted Desert Member. Within the

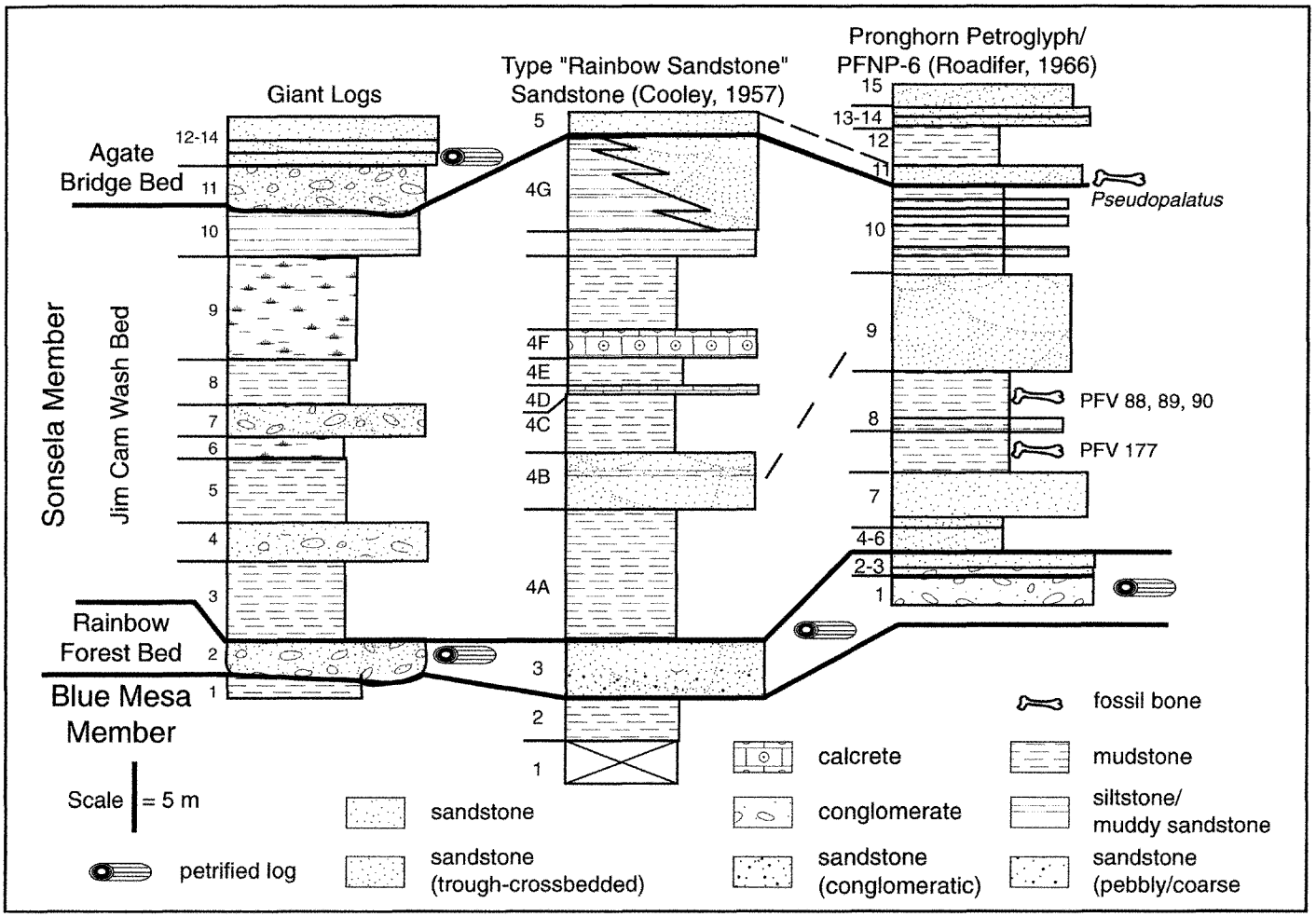

FIGURE 7. Type and reference sections of the Rainbow Forest, Jim Camp Wash, and Agate Bridge beds.

PFNP, the Sonsela most often crops out as a prominent ledge-former, such as at Blue Mesa, but locally may be incompetent, as at most of the "forests" in the southern portion of the park. The Sonsela is only present in the southern portion of the Painted Desert due to the gentle, northward regional dip.

There has been some confusion historically as to which sandstone bodies in the PFNP pertain to the Sonsela. The "Rainbow Sandstone" of Cooley (1957), as used by Akers et al. (1958), Cooley (1958, 1959), Billingsley (1985a,b), Ash (1987a), Murry (1990), Lucas (1994, 1995) and Heckert (1997) is actually the basal part of the Sonsela Member (Roadifer, 1966; Deacon, 1990). We name this bed the Rainbow Forest Bed below (Fig. 7). The stratigraphically complex interval from the base of the Sonsela to the top of "Flattops sandstone 1" (the Agate Bridge Bed of our usage) has been termed the Camp Wash Zone (Roadifer, 1966) or the Rainbow-Sonsela complex (Demko, 1994, 1995a,b). Our recent work clarifies these relationships.

We recognize here that the "Rainbow Sandstone" comprises the basal Sonsela, as identified by Deacon (1990). We also note that the next higher persistent sandstone, which forms the mesa top west of Jim Camp Wash and is traditionally assigned to "Flattops sandstone 1" (e.g., Billingsley, 1985a,b), actually represents an upper bed of the Sonsela. At its type section, the Sonsela consists of a tripartite sandstone-mudstone-sandstone division (Akers et al., 1958), with the medial mudstone portion strongly resembling the Blue Mesa Member in color and lithology (Lucas et al., 1997b). Therefore, we suggest that the beds variously identified as the Sonsela, Flattops 1, or top of the Camp Wash zone in fact represent the upper sandstone body of the Sonsela. Points of detailed similarity include sandstone lithotypes, bedforms, and colors, both fresh and weathered. In the PFNP, conglomeratic facies are rarer in this interval than in the lower Sonsela (Espegren, 1985; Deacon, 1990), a fact in accordance with our observations elsewhere (Lucas et al., 1997b). We note also that the mudstone deposits between the two sandstones are similar to those of the Blue Mesa Member. This similarity is doubtless one source of the confusion regarding the stratigraphic position of this interval, but is consistent with medial mudstones at both the type section of the Sonsela Member (Lucas et al. 1997b) and in numerous Sonsela sections in western New Mexico (Deacon, 1990; Heckert and Lucas, 1996, 2002; Heckert, 1997). Although this interval is stratigraphically thicker than most Sonsela mudstone intervals, the relatively thin sandstones below and above it yield a composite stratigraphic thickness (38.8 m) of the Sonsela very similar to that seen in the Zuni Mountains in west-central New Mexico, particularly in the vicinity of Thoreau (Deacon, 1990; Heckert and Lucas, 2002).

In order to explicate these stratigraphic relationships, both within the park and beyond it across the southern Colorado Plateau, we formalize the stratigraphic nomenclature of these beds. Therefore, we identify the tripartite division of the Sonsela Member as consisting of the basal, sandstone- and conglomerate-dominated Rainbow Forest Bed, a mudstone-dominated Jim Camp Wash Bed, and a sandstone- and conglomerate-dominated upper, Agate Bridge Bed. We utilize our Giant Logs stratigraphic section (Fig. 7) for type sections of all three beds, and describe

each in more detail in separate sections of the following text.

We are sensitive to the criticism that new names often only enhance existing stratigraphic problems, or even add new ones. However, two of the three names we formalize here (Rainbow Forest, Jim Camp Wash) have been in the literature for almost 50 years, and their lack of formal type sections has doubtless increased confusion resulting from their informal usage. The third name, the Agate Bridge Bed, is simply necessary because the only other previously used names for this unit are either used for units of higher stratigraphic rank (Sonsela) or would result in additional confusion (Flattops Bed 1).

Rainbow Forest Bed

We designate unit 2 of our Giant Logs section as the type section of the Rainbow Forest Bed (Fig. 7). We also designate unit 3 of Cooley's (1957) Rainbow Forest Sandstone as a reference section (Fig. 7). At the type section, the Rainbow Forest Bed consists of 2.25 m of white to pinkish-gray conglomeratic sandstone. The sandstone matrix is generally coarse- to very coarse-grained, moderately well-sorted, subangular quartzarenite. Conglomerate clasts consist primarily of quartzite and other siliceous pebbles, many as much as 3 cm in diameter. Rip-up clasts of light gray bentonitic mudstone are also common and locally up to 15 cm in diameter. This bed hosts the extensive "forest" of *Araucarioxylon* logs known as Giant Logs at the type section. At the nearby reference section in the Rainbow Forest, Cooley (1957, p. 253) described a thicker, but lithologically similar section of conglomerate and sandstone (~4.6 m thick).

These sections are dominated by Deacon's (1990) conglomeratic facies assemblage (see below), and his detailed work indicates that most of these strata were deposited in north- or northeasterly-flowing streams. Indeed, Deacon (1990) measured more than 6 m of massive tabular conglomerate and trough-crossbedded sandstone at the Rainbow Forest.

Presently, the only fossils known from the Rainbow Forest Bed are petrified logs, principally of *Araucarioxylon* (e.g., Fig. 8B), but including very rare trunks of *Schilderia* and *Woodworthia* (Ash, 1987a; Heckert and Lucas, 1998b; Ash and Creber, 2000). This is the main wood-bearing horizon, both inside and outside of the park (Heckert and Lucas, 1998b). Ash (1987a) and Ash and Creber (2000) noted that almost all petrified logs at PFNP lack bark, apparently as a result of abrasion during transport. Consequently, relatively few of the logs within the park actually grew there—most were instead transported from the source areas to the south and west. The trees throughout the type area of the Rainbow Forest Bed typically point to the northeast in accordance with crossbed and other paleoflow indicators (Heckert and Lucas, 1998b).

Billingsley (1985b) mapped the Rainbow Forest Bed as the "Rainbow Sandstone" (rss) throughout the southern portion of the park. In the middle and northern portions of the park, he mapped it as the Sonsela Sandstone Bed (Trcps).

Jim Camp Wash Bed

We designate beds 3-10 of our Giant Logs section as the type section of the Jim Camp Wash Bed (Fig. 7). Here, we measured 29.9 m of interbedded bentonitic mudstone and lithic sandstone, with lesser amounts of conglomerate and calcrete nodules. These strata collectively form the less-resistant slope-forming, finer-grained "middle" of the Sonsela Member between the more resistant Rainbow Forest and Agate Bridge beds (Fig. 8A). Basal Jim Camp Wash Bed strata are gradational with the underlying Rainbow Forest Bed, and apparently mark the transition from channel- and lag deposits to primarily floodplain deposition. Indeed, Jim Camp Wash Bed strata strongly resemble the mudstones of the Blue Mesa Member beneath the Rainbow Forest Bed, and in areas of limited outcrop where the Rainbow Forest Bed is not visible it is difficult to distinguish the two units. Generally, mudstones of the Jim Camp Wash Bed are slightly redder (grayish red-purple and pale red-purple) than the bluish gray and grayish purple mudstones of the Blue Mesa Member. Coarser-grained strata of the Jim Camp Wash Bed are texturally immature lithic sandstones and, locally, conglomerates. Some of these beds can be traced for several kilometers, but none are as persistent as either the Rainbow Forest Bed or the Agate Bridge Bed (Figs. 4, 7). Locally these strata are trough crossbedded and may bear minor amounts of petrified wood. Generally, Jim Camp Wash Bed strata appear to represent an interval of relatively rapid aggradation during Sonsela time. Billingsley (1985a) mapped the type area of the Jim Camp Wash Bed as either part of his "Rainbow Sandstone" ("rss," apparently undifferentiated) or as the upper portion of the Petrified Forest Member (Trcpu).

To date, few fossils are known from the Jim Camp Wash Bed. Comparison of Billingsley's (1985a) geologic map to localities plotted by Evanoff (1994; see also Parker, 2002) and described by Long and Murry (1995) indicate that a fragmentary vertebrate fauna, including the aetosaur *Typothorax*, is present in these beds. These fossils, especially *Typothorax coccinarum*, indicate a Revueltian (early-mid Norian) age for the Jim Camp Wash Bed, an assignment consistent with age determinations for the Sonsela elsewhere obtained from pollen (Litwin et al., 1991), megafossil plants (Ash, 1980) and other fossils, principally vertebrates (Lucas, 1997, 1998).

Agate Bridge Bed

We designate units 11-15 of our Giant Logs section the type section of the Agate Bridge Bed (Fig. 7). Units 7-11 of Murry and Long's (1989) section "north of Agate Bridge," reproduced here in Figure 4, serve as a reference section, and the excellent outcrops along the road there were studied extensively by Deacon (1990) as well.

At the type section we measured 6.6 m of sandstone with minor amounts of conglomerate. The basal contact is sharp and erosional, scouring at least 1 m into the underlying beds locally. The upper contact of the Agate Bridge Bed is often a stripped surface, but is clearly gradational with the overlying Painted Desert Member mudstones. At the type section, most Agate Bridge Bed sandstones are yellowish gray to light olive gray and moderate yellowish-brown, trough-crossbedded quartzarenites. In a general sense the coarsest sandstones are at the base of the unit and are poorly sorted, ranging from fine- to very coarse-grained. Stratigraphically higher sandstones are moderately well sorted and fine- to medium-grained. Conglomerates have a matrix of lithologically similar sand supporting mostly intraformational limestone (calcrete) and mudstone rip-up clasts. Siliceous pebbles are less common in the Agate Bridge Bed than in the Rainbow Forest Bed. Bedforms are dominated by trough crossbeds and scour-and-fill structures, but also include planar crossbeds and horizontal stratification (Espegren, 1985). Finer-grained ripple laminated sandstone and siltstone are also locally present. Paleocurrents measured by Espegren (1985) are inconsistent, and variously indicate predominantly SSE, NNW and NW-directed flow. Espegren (1985) interpreted these strata, (typically termed Flattops Sandstone 1) as representing the deposits of a braided (low sinuosity) fluvial system that was dominated by a sandy bed load. These interpretations are consistent with the hypothesis that the Agate Bridge Bed is an upper bed of the Sonsela, as this interpretation is very similar to that reached by Deacon (1990) for lower Sonsela strata.

The only known fossils from the Agate Bridge Bed are petrified logs and, locally, unionid bivalves. Units 11 and 12 of the

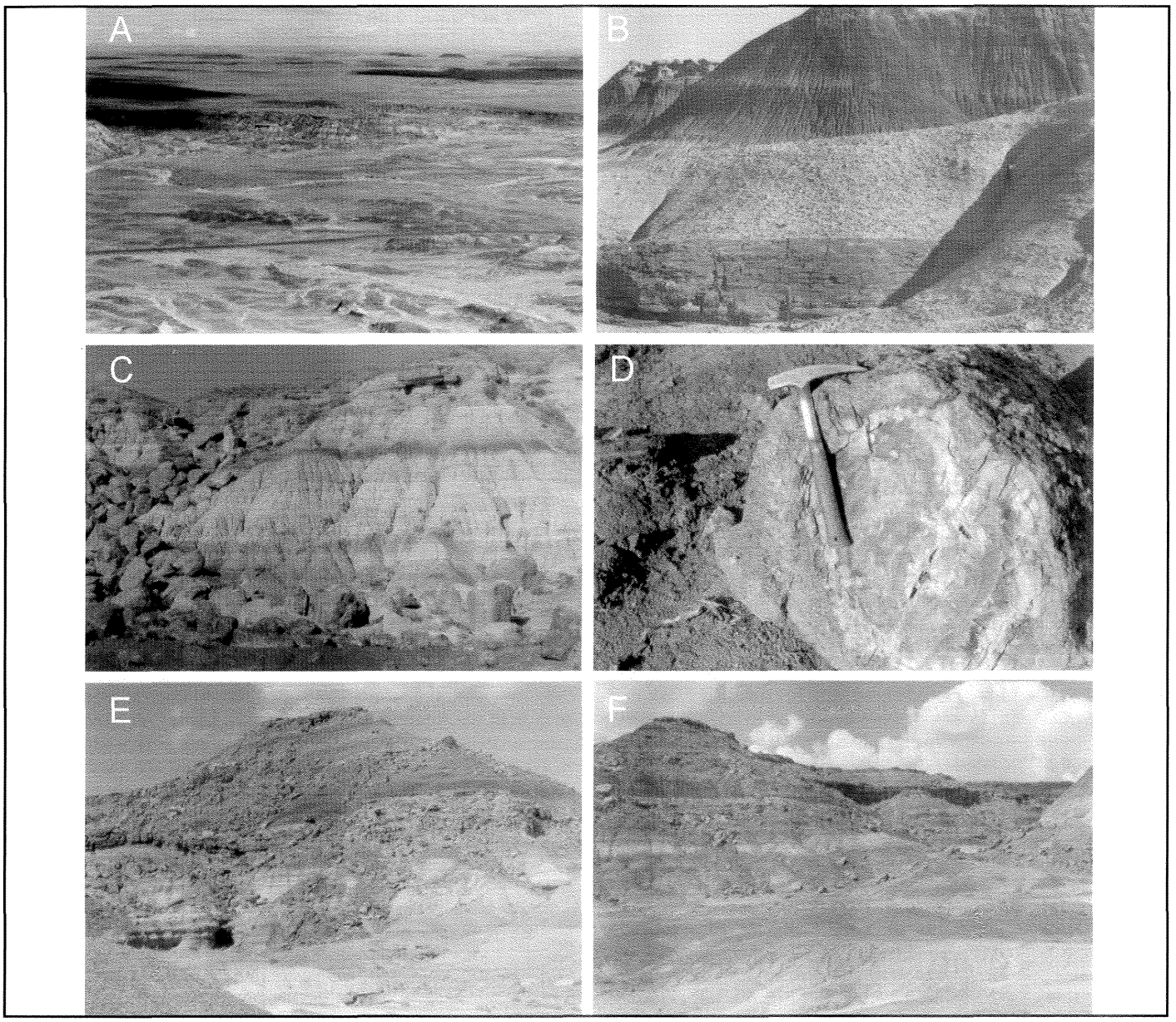

FIGURE 8. Photographs of Sonsela Member and lower Painted Desert Member strata in the southern PFNP. **A**, Aerial photograph to the northwest overlooking Jim Camp Wash and showing broad exposures of Jim Camp Wash Bed of the Sonsela Member. **B**, Close-up of *Araucarioxylon* weathering out of Rainbow Forest Bed of the Sonsela Member at Long Logs; **C**, Sonsela Member exposures at Jasper Forest (section PFNP-10 of Roadifer, 1966). **D**, Close-up of typical petrified log of *Araucarioxylon* exposed at Jasper Forest. **E**, View to the east of the eastern Flattop, Flattops Bed 4 caps the mesa, Flattops Bed 3 crops out just below the light interval (note prominent knob on east (right) slope, and Flattops 2 is the prominent sandstone in the foreground. **F**, View to the north of the eastern flattop; Flattops Bed 2 is the most prominent sandstone (foreground), Flattops Bed 3 forms a discrete ledge in the left-center of the photograph, and Flattops Bed 4 caps the mesa.

type section bear some petrified wood, which is typically shades of yellow, brown and gray and readily distinguished from most of the much more brightly colored logs of the stratigraphically lower Rainbow Forest Bed (Heckert and Lucas, 1998b).

In the southern portion of the park, Billingsley (1985a) generally mapped the Agate Bridge Bed as "Flattops Sandstone 1" (1ss). In the northern part of the park, we consider beds mapped by Billingsley (1985b) as "Painted Desert Sandstone 1" (1ss) in section 7, T19N, R24E as the uppermost Sonsela and thus likely the Agate Bridge Bed. Sandstones south of there mapped as "1ss" are apparently a drafting error and actually equivalent to the Lithodendron Wash Bed of the Painted Desert Member (see below), mapped as "2ss" elsewhere in the vicinity of Lithodendron Wash.

Sonsela Lithology and Interpretation

Deacon (1990) recognized conglomerate, sandstone and mudstone-dominated facies assemblages within the Sonsela in the PFNP, and we have built upon his descriptions to describe the units here. Basal Sonsela Member strata are characteristically white to pinkish gray fresh, and weather to light gray and yellowish gray. Conglomerate clasts are typically extraformational chert pebbles that are dominantly moderate yellowish brown and as much as 15 cm long. Intraformational clasts are locally common and consist of grayish-blue to grayish-purple mudstone clasts up to 20 cm long derived from the underlying Blue Mesa Member. Conglomerates usually fill shallow scours and may possess rudimentary stratification to cross stratification.

Sonsela Member sandstones vary from very fine-grained to conglomeratic, but are typically fine- to medium-grained, subrounded to subangular, well-sorted quartzarenites, although some sandstones are sufficiently muddy that they are wackes instead of arenites (Espegren, 1985; Deacon, 1990). Deacon (1990) recognized quartzose and volcanic lithic petrofacies within the Sonsela sandstones, with the latter most prevalent within the PFNP. Sonsela sandstones are typically coarser, more angular and more poorly sorted within the sand-sized fraction than sandstone beds higher and lower in the Petrified Forest Formation. They are, however, more compositionally mature, consisting principally of quartzarenites and clean sublitharenites with much less muddy or ashy matrix than underlying sandstone bodies in the PFNP. Sandstones of the Sonsela Member are typically trough crossbedded, but are locally ripple laminated, laminated, planar crossbedded or structureless.

The Sonsela was deposited in a series of channels that trended north to northeast across the southern Colorado Plateau. Kraus and Middleton (1987) and Deacon (1990) both interpreted this as a low-sinuosity channel complex. Paleocurrent measurements indicate northeast flow of this river system both within (Espegren, 1985; Deacon, 1990) and immediately outside (Poole, 1961; Heckert and Lucas, 1998b) the PFNP.

The Sonsela Member is the primary wood-bearing unit within the park and its immediate surroundings, and produces almost all of the brightly colored "rainbow" petrified wood (Heckert and Lucas, 1998b). Petrified logs are especially abundant at Giant Logs, Rainbow Forest, Long Logs (Fig. 8B), Jasper Forest (Fig. 8C-D), Crystal Forest, and Blue Mesa in the southern PFNP, with lesser amounts of wood weathering out in Jim Camp Wash and at Agate Bridge. Petrified wood is less abundant in the northern part of the park, but is locally abundant in Wildhorse Wash and Lithodendron Wash. Heckert and Lucas (1998b) described the stratigraphic distribution of petrified wood in the PFNP in greater detail. Generally the most colorful petrified logs weather out of the Rainbow Forest Bed. These include the vast majority of the variegated red, orange, purple, black, blue, and green logs. Logs weathering out of the stratigraphically higher Agate Bridge Bed are generally duller and typically weather to shades of grayish white and brownish yellow.

The Sonsela fills scours in the underlying Blue Mesa Member (Figs. 4, 7), a relationship that has long been recognized both locally in the PFNP and regionally across the southern Colorado Plateau (Cooley, 1957; Akers et al., 1958; Roadifer, 1966; Stewart, et al., 1972a; Billingsley, 1985a; Espegren, 1985; Deacon, 1990; Murry, 1990; Lucas, 1993). Lucas (1993) identified this unconformable surface as the Tr-4 unconformity, and Heckert and Lucas (1996a) demonstrated that farther to the east the Blue Mesa Member was completely removed by erosion during development of this unconformity. Locally, Deacon (1990) observed as much as 7 m of scouring and erosion by the Sonsela into underlying strata in the vicinity of the PFNP. Numerous lines of biochronological evidence, including tetrapod fossils (Long and Padian, 1986; Murry and Long, 1989; Murry, 1990; Hunt and Lucas, 1993b, 1995; Lucas, 1993, 1994a, 1995, 1997; Lucas and Hunt, 1993a,b; Long and Murry, 1995), palynology (Litwin et al., 1991), calcareous microfossils (Kietzke, 1989; Lucas and Kietzke, 1993), and plant megafossils (Ash, 1980, 1987a,b) demonstrate that strata below the Sonsela Member are of late Carnian age and strata that overlie the Sonsela are of Norian age, demonstrating that the Tr-4 unconformity encompasses the Carnian-Norian boundary in the American Southwest.

Painted Desert Member

The Painted Desert Member is the stratigraphically highest member of the Petrified Forest Formation, and crops out extensively in the northern PFNP, but is restricted to the general area of the Flattops and exposures to the north and west along a topographic feature informally known as "Martha's Butte" in the southern PFNP. The basal contact is gradational with the underlying Sonsela Member, and the upper contact is sharp but conformable with the overlying Owl Rock Formation. The type section of the Painted Desert Member in the northern PFNP is 147.2 m thick (Lucas, 1993) and consists primarily of pale- to grayish-red mudstone with numerous sandstone beds expressed locally as thin, persistent benches (Lucas, 1993). Some of these sandstones are sufficiently persistent that they are mappable stratigraphic units, and we designate them as bed-level units in the following sections. In the southern portion of the PFNP, outcrops of the Painted Desert Member are limited to the Flattops area (Figs. 8E-F, 9-10) and "Martha's Butte" (sections 17-18, 20, 29, T17N, R24E). In this area, we refer sandstones in the Painted Desert Member to Flattops Beds 2-4 (in ascending order) (Figs. 9-10). As explained in the earlier section on the Sonsela Member, strata assigned by Billingsley (1985a,b) to "Flattops Sandstone 1" are best referred to the Sonsela, not the Painted Desert, so there is no bed we identify as "Flattops Bed 1." North of I-40, extensive outcrops of the Painted Desert Member occur in the Painted Desert, where Ash (1992) named the Black Forest Bed, and we recognize the Lithodendron Wash Bed as formal stratigraphic units (Figs. 11-13).

Flattops Beds

Exposures of the Painted Desert Member in the southern PFNP are limited to a band stretching from the southeast corner of the park northwestward through the Flattops and then north and west through Martha's Butte past the park boundaries (Billingsley, 1985b). Three stratigraphically superposed sandstone-dominated, persistent ledges occur above the Sonsela Member in this area. These have historically been termed the "Flattops Sandstones" (e.g., Roadifer, 1966; Billingsley, 1985a,b; Ash, 1987a), but no type sections were ever designated. Here, we formalize these terms as Flattops Beds 2-4 (Fig. 9).

Flattops Bed 2

We designate units 8-11 of our Flattops west section, in the NE1/4 NE1/4 sec. 31, T17N, R24E, as the type section of Flattops Bed 2 (Fig. 9), with various sections reported by Cooley (1957), Roadifer (1966), and Murry and Long (1989) at the Flattops in section 32 serving as excellent reference sections (Figs. 8E-F, 10). At the type section, Flattops Bed 2 is 6.6 m thick (Fig. 9). At the reference sections this unit is as much as 11.4 m thick (Roadifer, 1966; Fig. 10). The basal contact is frequently erosional, with scours filled by intraformational conglomerate composed primarily of calcrete nodules ripped up from underlying strata. The upper contact has been removed by erosion at the type and many other sections, but is clearly gradational, with the sandstone beds fining upward into red-bed mudstone deposits. In spite of extensive variations in thickness laterally, Flattops Bed 2 is laterally continuous and readily traceable across much of the Flattops area. Indeed, Billingsley (1985b) mapped Flattops Bed 2 (as "2ss") north and west at least as far as Twin Buttes outside the park in sec. 28, T18N, R23E (Billingsley, 1985b; Espegren, 1985).

At the type section, Flattops Bed 2 consists primarily of brownish-gray to light brownish-gray, very fine- to medium-grained, subrounded, well-sorted subarkose. Locally, there are numerous lenses of intraformational conglomerate. Conglomerate clasts are principally intraformational mudstone rip-ups. Sedimentary structures consist primarily of trough- and planar crossbedding, although horizontal and ripple laminae are also

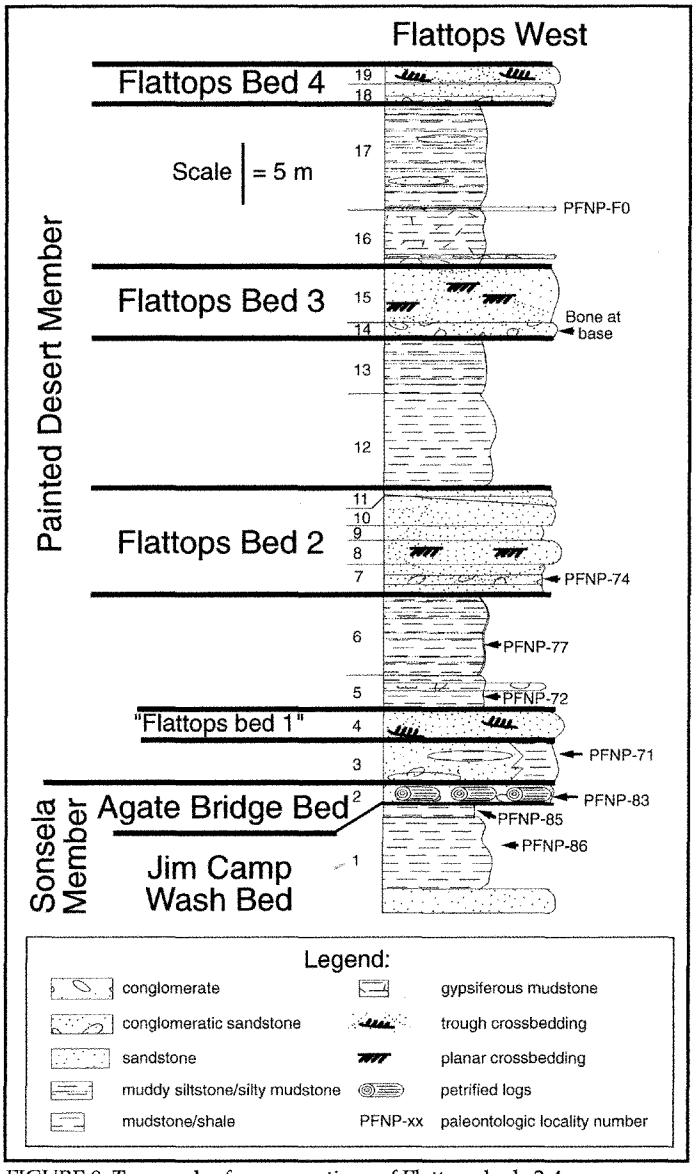

FIGURE 9. Type and reference sections of Flattops beds 2-4.

common. Espegren (1985) reported that planar crossbedded strata occur as either thick (meter-scale) tabular sets that are interbedded with other sandstone facies or else as thinner, multistoried sets. Trough crossbedding features described by Espegren (1985) include both tabular and lenticular bodies. Paleocurrent studies indicate primarily northwesterly flow for Flattops Bed 2 (Espegren, 1985, fig. 88c). Espegren (1985) interpreted Flattops Bed 2 as representing the deposits of a high sinuosity fluvial system with mixed bed and suspended loads. Fossils are relatively uncommon and limited to isolated beds of unionid bivalves, which typically indicate continuous flow or agitation of the water (Good, 1993a,b).

Flattops Bed 2 is extremely persistent laterally and strongly resembles the Lithodendron Wash Bed in the Painted Desert to the north (described below). Fine- to medium-grained, planar crossbedded sandstone beds are common in the lower Painted Desert Member and correlative strata (Cooley, 1957) and include the Perea Bed near Fort Wingate (Cooley, 1957; Lucas et al., 1997a) and the Saladito Point Bed in the Bull Canyon Formation in east-central New Mexico (Lucas et al., 2001). Whether these beds represent a regional response to base level changes as does the Sonsela Member, or are genetically independent of each other is unclear, but we note here that these units typically share numerous lithologic features and sedimentary structures and thus were deposited by similar fluvial systems.

Flattops Bed 3

We designate units 14-15 of our Flattops west section (SW1/4 NW1/4 sec. 32, T17N, R24E) as the type section of Flattops Bed 3 (Fig. 9), and identify the sections of Cooley (1957), Roadifer (1966) and Murry and Long (1989) at the eastern Flattops as reference sections (Fig. 10). At the type section, Flattops Bed 3 is 6.2 m thick (Fig. 9). Minor scours under 1 m in depth are present in the underlying sandy mudstone, and the unit grades upward into fine-grained strata. Generally, this bed is restricted to prominent cliffs and benches in the slopes of the Flattops mesas in sec. 32, T17N, R24E.

At the type section, Flattops Bed 3 consists primarily of yellowish-gray to brownish-gray, very fine- to fine-grained, subrounded, well-sorted sublitharenite overlying a basal olive-gray to yellowish-gray, fine- to coarse-grained, conglomeratic quartzarenite. Conglomerate clasts are primarily intraformational limestone (calcrete) clasts, with some chert pebbles of probable extraformational origin. The basal conglomerate unit is up to 1.3 m thick and graded, with conglomerates occurring primarily as lags in trough scours. The overlying sandstone is planar crossbedded, plane-bedded, or massive, with lesser amounts of trough crossbedding. Espegren (1985) reported that most crossbedded strata occur as multistoried sets. Paleocurrent studies indicate primarily southwesterly flow with a secondary component of northwesterly flow (Espegren, 1985, fig. 88d). Like Flattops Bed 2, Espegren interpreted this unit as representing deposition of high-sinuosity, mixed load, fluvial sediments. Unionid bivalves are more common in this unit than in Flattops Bed 2.

Flattops Bed 3 is present only very locally, and only Roadifer (1966) correlated these deposits to beds outside the park, where it crops out on an isolated mesa in the SW1/4 of sec. 25, T18N, R23E. Otherwise, this unit is restricted to the Flattops area. Billingsley (1985b) did not map Flattops Bed 3 ("3ss") outside of the park.

Flattops Bed 4

We designate units 18-19 of our Flattops west section (SW1/4 NE1/4 NW1/4, sec. 32, T17N, R24E) as the type section of Flattops Bed 4 (Fig. 9), and identify the sections of Cooley (1957), Roadifer (1966) and Murry and Long (1989) at the eastern Flattops as reference sections (Fig. 10). At the type section, Flattops Bed 4 is at least 3.4 m thick (Fig. 9). The thickest section is Cooley's (1957) PF-23A section, which records 3.9 m of sandstone (Fig. 10). The basal contact is sharp and irregular, with some scour-and-fill in the underlying mudstones. The upper contact is not preserved, as these beds cap the Flattops mesas and are not traceable outside of sec. 32, T17N, R24E.

The base of the type section of Flattops Bed 4 consists of 1.8 m of pale red to grayish red, very fine- to fine-grained, subrounded, well-sorted micaceous quartzarenite locally interbedded with a cherty mudstone-pebble conglomerate of similar colors. Overlying sandstones are at least 1.6 m thick and consist of pale red, pinkish-gray, and light gray sandstones of similar lithology. Trough crossbedding is common, along with lesser amounts of horizontal and ripple-laminated strata. Espegren (1985) reported both tabular bodies and sheets of trough-crossbedded strata. Paleocurrent studies indicate southeasterly flow (Espegren, 1985, fig. 88e). Because of the limited outcrop distribution of this unit, Espegren (1985) only tentatively suggested that Flattops Bed 4 represents the deposits of a mixed- to bed load-dominated, high sinuosity fluvial system.

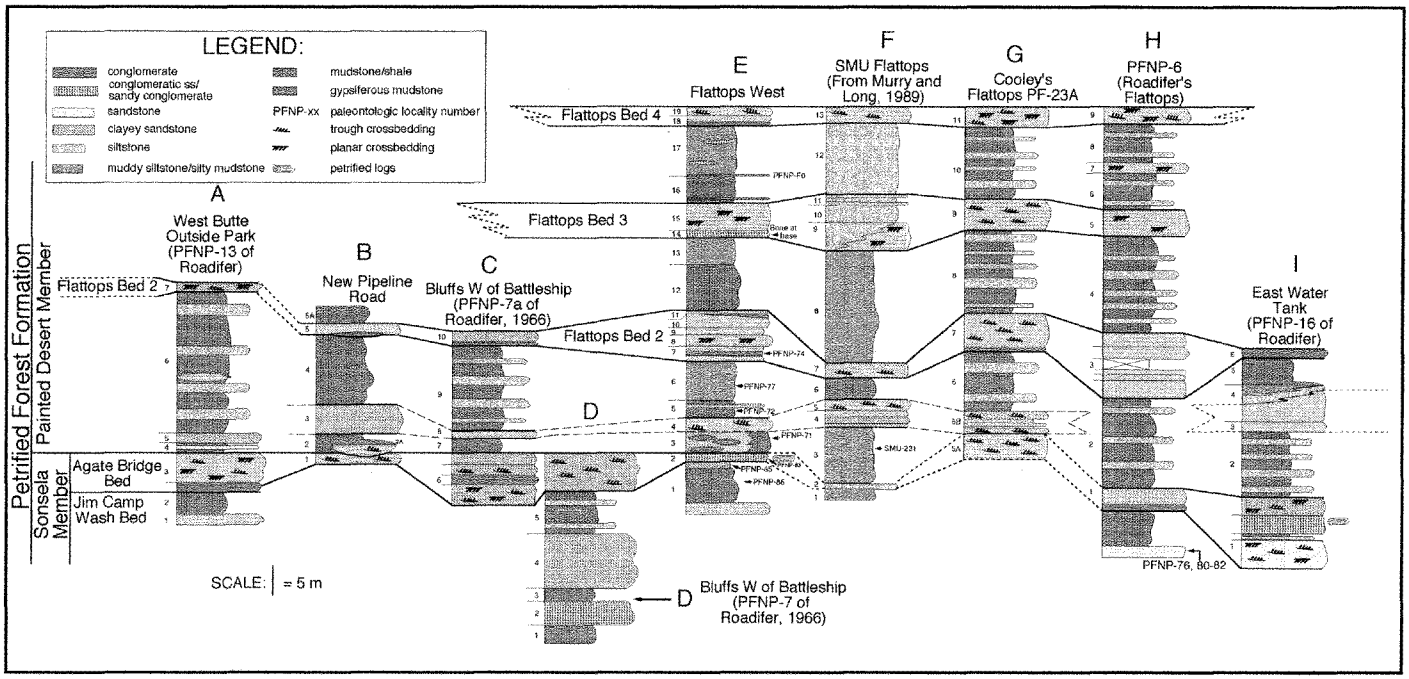

FIGURE 10. Measured stratigraphic sections of the Flattops beds in the PFNP and vicinity.

Painted Desert Member bed-level units in the Painted Desert

Billingsley (1985b) identified two mappable Painted Desert sandstones and the "Black Forest Tuff" on his geologic map of the PFNP. However, in a separate paper he (Billingsley, 1985a) introduced a third sandstone unit, for a total of four sandstone beds in the Painted Desert (Fig. 3). Only one of the lower sandstones, traditionally referred to as 2 or 3, is consistently present in the PFNP (Fig. 11). Here, we continue to formalize the stratigraphy mapped by Billingsley (1985b) and identify this unit as the Lithodendron Wash Bed (Fig. 13). We also follow Ash (1992), who formalized the Black Forest Bed as 10.6 m of limestone-pebble conglomerate and reworked tuff, in recognizing the Black Forest Bed as a distinctive lithologic unit on which we hang our Painted Desert measured sections (Fig. 11).

Lithodendron Wash Bed

We designate units 8-9 of our Chinde Point II section (NW1/4 SE1/4 NE1/4, sec. 33, T20N, R24E) as the type section of the Lithodendron Wash Bed (Fig. 13). Many of the mesas and buttes in the Painted Desert along the margins of Lithodendron Wash and northward across the Painted Desert are developed in this unit (Figs. 11, 12A,D,F). At the type section, the unit is 2.5 m thick, although its thickness is highly variable across the Painted Desert. At the topographic feature informally known as "Petroglyph Mesa" we measured 7.6 m of strata we assign to the Lithodendron Wash Bed (Fig. 7.6). This unit has often been referred to as Painted Desert Sandstone 2 or 3. For example, Billingsley (1985b) consistently maps this unit as Painted Desert Sandstone 2 ("2ss"), yet refers to it as "Painted Desert Sandstone 3" in his (1985a) summary of PFNP stratigraphy. Additionally, the apparent drafting error mentioned previously confuses the issue further, as this sandstone is mapped as "1 ss" south of section 7, T19N, R24E.

Typically, the Lithodendron Wash Bed consists of alternating bands of pale greenish-yellow and pale red, very fine- to fine-grained, subangular to subrounded, moderately well-sorted sublitharenite. Locally, some conglomerates, consisting primarily of mudstone rip-up clasts derived from underlying strata, are present in trough-shaped channels at the base of the unit. The color banding is especially prominent in well-defined lateral accretion sets of planar crossbeds, and some trough crossbedding is also evident.

This is not the only sandstone of this lithotype in the Painted Desert; indeed, as many as three other sandstone beds of this lithotype can be observed in the vicinity of Chinde Point (Fig. 13). However, of these sandstones, only the Lithodendron Wash Bed is persistent throughout the Painted Desert. The Lithodendron Wash Bed is easily correlated across the Painted Desert and forms the mesa tops on the features informally dubbed "Petroglyph Mesa" (S1/2 SE1/4 sec. 13 T20N R23E) and "Boot Ridge" (NE1/4 NW1/4 sec. 18, T20N R24E) as well as a prominent bench beneath Chinde and Kachina points at the type section (Figs. 11, 12A).

Black Forest Bed

The Black Forest Bed, as defined by Ash (1992), crops out throughout the northern Painted Desert as a pinkish and pinkish-gray band as much as 12.6 m thick (Figs. 11, 12B-C). The lower contact is sharp and erosional. The upper contact is also sharp and marked by a transition from pinkish sandstone and reworked tuff to reddish brown and brownish red bentonitic mudstones. Ash (1992) informally divided the Black Forest Bed into upper and lower portions, an upper portion dominated by reworked tuff, and a basal conglomeratic unit typified by calcrete-pebble conglomerate. Outcrops of the Black Forest Bed in the PFNP are constrained to the Painted Desert area; west of the Black Forest proper, this bed appears to pinch out (Ash, 1992). To the south the Painted Desert Member has been eroded below the stratigraphic level of the Black Forest Bed (Fig. 11). Ash (1992) noted the presence of 4.2 m of reworked tuff he considered correlative to the Black Forest Bed 20 km east of the PFNP. Otherwise, this unit has no apparent correlatives outside the PFNP.

At its type section, the Black Forest Bed consists of 7.7 m of well-indurated calcrete-pebble conglomerate (1.4 m) and softer, less well-indurated reworked tuff (6.3 m) (Fig. 11). Locally, calcrete clasts range up to cobble sized (Ash, 1992), and this unit contains abundant petrified wood debris, particularly within the Black

Forest proper. The upper unit is principally reworked, andesitic tuff pyroclasts with thin interbeds of mudstone and siltstone of more typical Painted Desert Member lithotypes (Ash, 1992). Petrographic studies reported by Ash (1992) demonstrated that this unit consists of over 50% reworked tuff. Disparate dates, 239±9 and 207±2 Ma, were assigned to the Black Forest Bed by K-Ar (Ash, 1992) and U-Pb dating methods (Riggs et al., 1994a), respectively, and are discussed later in this paper.

The Black Forest Bed has the most distinctive and identifiable volcaniclastic component of any stratigraphic unit in the Chinle Group (Stewart et al., 1972a; Ash, 1992). However, the source of the tuffaceous material remains unknown, as does the source of the bentonitic material in Chinle mudstones generally (Stewart et al., 1972a, 1986)

The upper portion of the Black Forest Bed is richly fossiliferous in fossil logs, vertebrates, and bivalves. Petrified wood in the Black Forest is predominantly *Araucarioxylon*, but also includes most of the *Woodworthia* and *Schilderia* from the Petrified Forest area, as these taxa are much more abundant here than elsewhere in the park. All petrified wood from the Black Forest Bed is heavily silicified and, generally, black in color, giving the Black Forest its name. This is the stratigraphically highest abundant petrified wood horizon within the park (Heckert and Lucas, 1998b) and also marks the stratigraphic upper limit of extensive vertebrate fossil collections.

Owl Rock Formation

The Owl Rock Formation in PFNP consists of as much as 36.6 m of mudstone, sandstone, siltstone and pisolitic limestone (Billingsley, 1985a; Lucas, 1993; Fig. 11). These strata conformably overlie the Painted Desert Member and are overlain unconformably by the Neogene Bidahochi Formation (Baskin, 1979; Billingsley, 1985a,b) within the park. The base of the Owl Rock Formation is traditionally placed at the first persistent limestone bed, and in the PFNP this is an 0.8-m-thick pisolitic limestone cropping out on the slopes of Chinde Mesa in the northern PFNP. Due to the gentle northward regional dips, this is the only area where the Owl Rock Formation crops out within the park.

The Owl Rock Formation is extremely heterolithic. A section reported by Lucas (1993) is dominantly mudstone (41%) and sandstone (41%) with minor pisolitic limestone (12%) and siltstone (6%). Clastic lithologies of the Owl Rock Formation in the PFNP are difficult to distinguish from underlying Painted Desert strata. Mudstones are bentonitic, pale red to orange-pink, and contain gray chalcedony nodules. Siltstones are reddish-orange to reddish-brown, and sandstones are pale red to pale reddish-brown, very fine-grained, well-sorted, trough-crossbedded litharenites. Tanner (2000) interpreted siliciclastic strata of the Owl Rock Formation in Utah and Arizona as having been deposited in typical Chinle depositional environments, principally sinuous

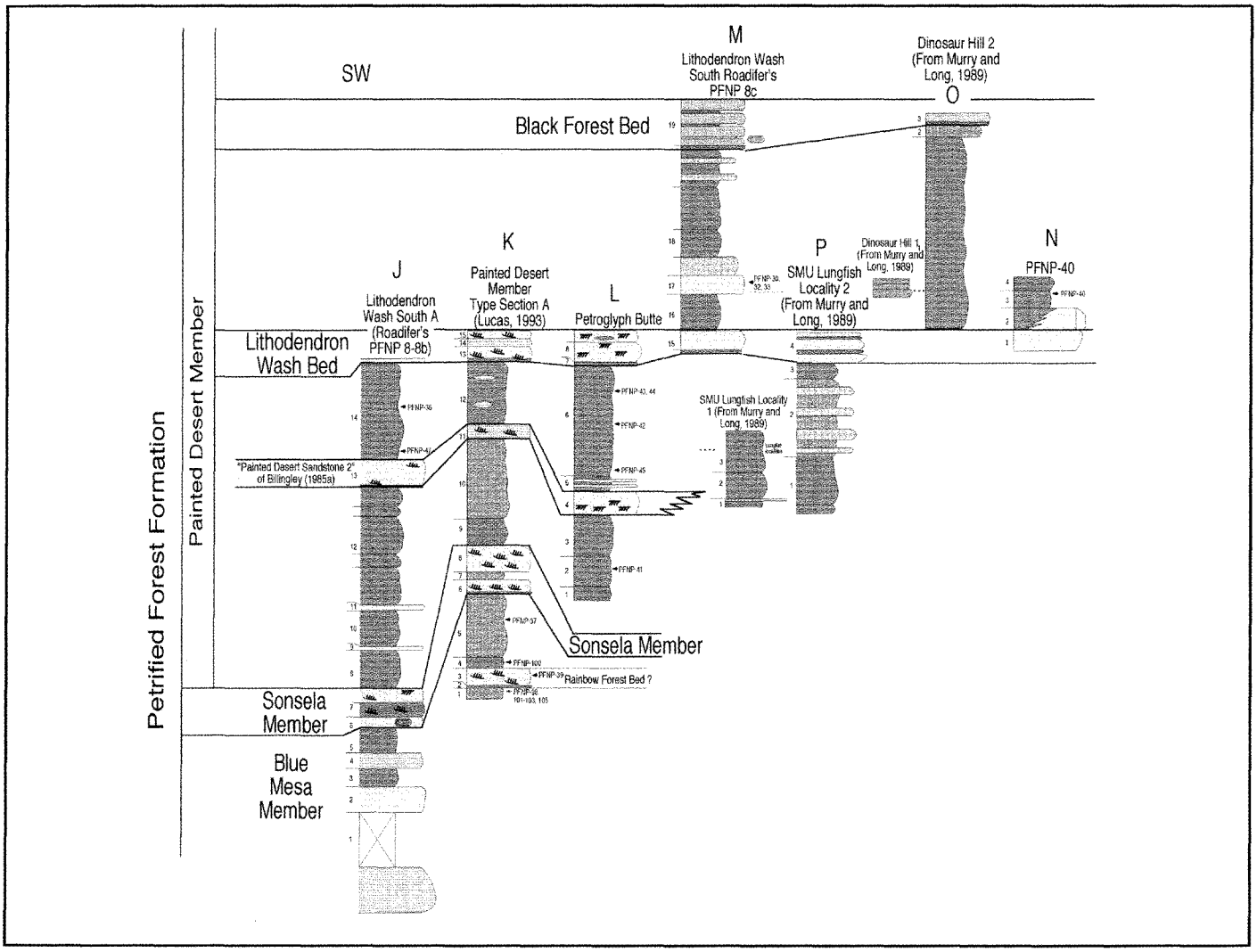

FIGURE 11A . Measured stratigraphic sections of the Petrified Forest Formation in the Painted Desert and vicinity, PFNP.

streams and muddy floodplains subjected to occasional sheetfloods.

The limestones of the Owl Rock Formation are both the defining feature of the unit and the source of some debate. Historically, the Owl Rock Formation was thought to have a lacustrine origin (Blakey and Gubitosa, 1983; Dubiel, 1989a,b, 1993). This interpretation was based on exposures of limestone with ostracodes, lamination and bioturbation and ripple-laminated upper surfaces. Although there are facies of the Owl Rock Formation that contain these features, Owl Rock Formation limestones exposed at the PFNP and many other places consist of markedly different lithotypes. In the PFNP, Owl Rock Formation limestones

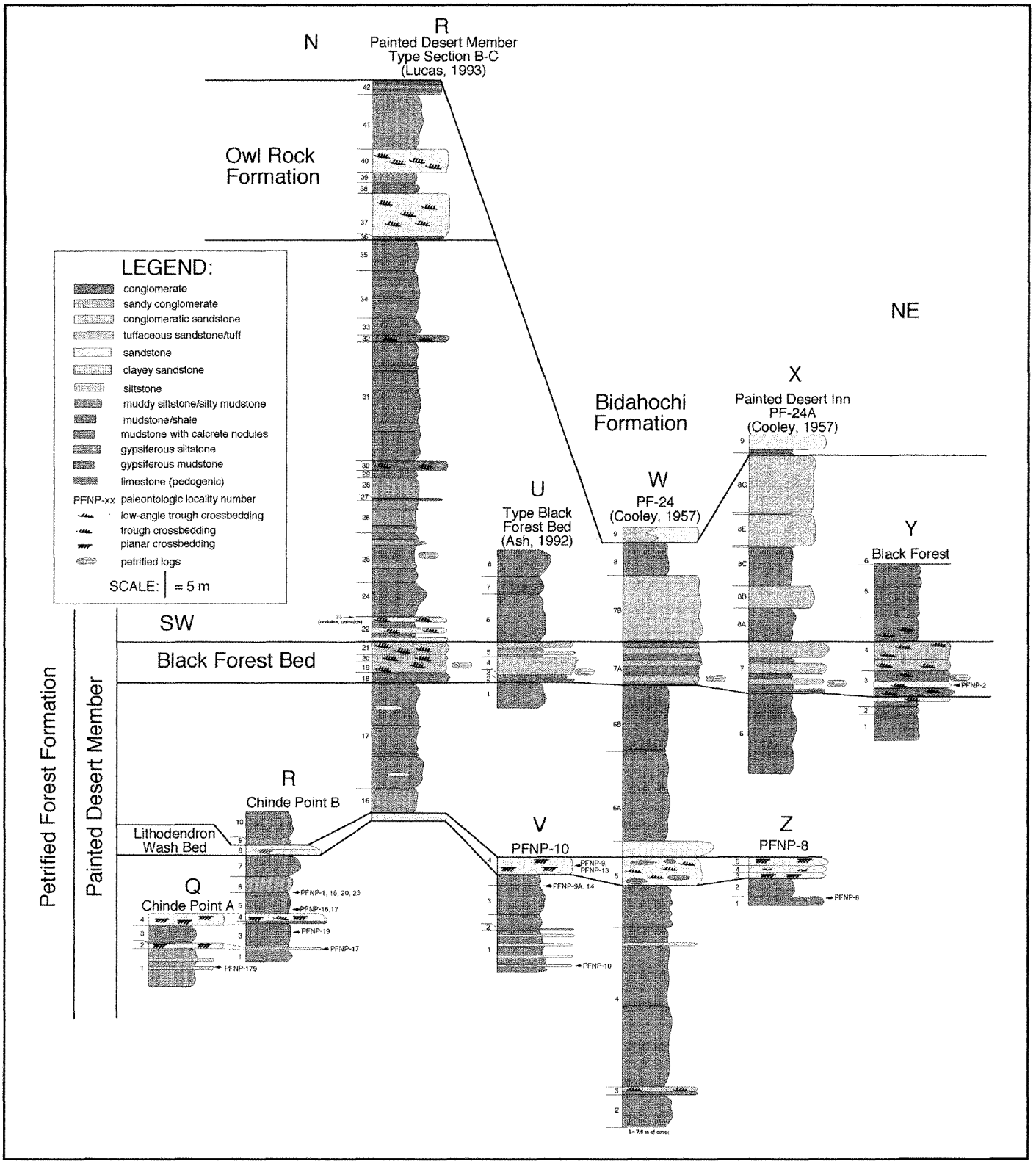

FIGURE 11B. Measured stratigraphic sections of the Petrified Forest Formation in the Painted Desert and vicinity, PFNP.

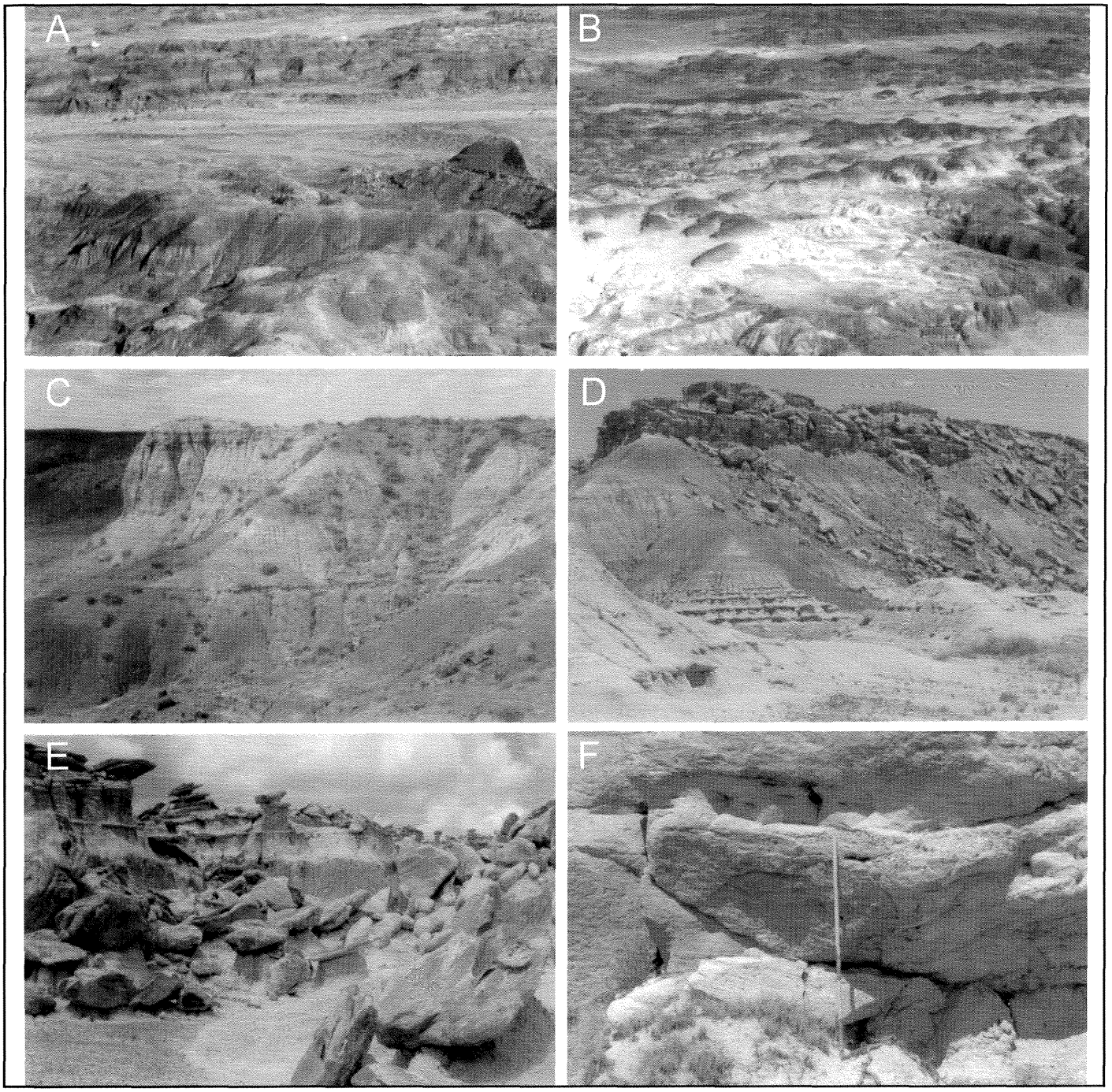

FIGURE 12. Photographs of Sonsela Member and lower Painted Desert Member strata in the vicinity of Lithodendron Wash in the northern PFNP. **A**, aerial photograph to ~west of Lithodendron Wash and Painted Desert Member strata. **B**, Aerial photograph of the Black Forest Bed (foreground) and uppermost Painted Desert Member strata in the vicinity of the Black Forest. **C**, Painted Desert Member strata and Black Forest Bed near Lacey Point. **D**, Kachina Point Bed overlying red-beds of the Painted Desert Member near "Petroglyph Butte" in the Painted Desert. **E**, Hoodoos west of Lithodendron Wash developed in the Sonsela Member. **F**, Incised channel fill of the Sonsela Member in the southwest corner of the Painted Desert.

are pisolitic, massive, and color mottled, with some nodular textures and mud chips. Other features of Owl Rock Formation limestones at the PFNP and elsewhere include great thickness and lateral persistence, tabular to platy structures, pisolitic to multilaminar internal fabric, secondary-silica, dissolution zones, brecciation, and recementation. Lucas and Anderson (1993) noted that these features were used by Gile et al. (1966) and Bachman and Machette (1977) to define stage III to stage VI calcretes. We agree with Lucas and Anderson (1993) and recognize a pedogenic origin for Owl Rock Formation limestones in the PFNP.

Tanner (2000) recently reviewed the sedimentology of the Owl Rock Formation on the Colorado Plateau and concluded that most Owl Rock limestones represent small, ephemeral to perennial, lakes and ponds that were subsequently overprinted by extensive pedogenesis. Pedogenesis (as indicated from the maturity of calcrete profiles) increases upwards in the stratigraphic section, apparently indicating increasing aridification associated with northward drift of the Chinle basin during the Late Triassic (Tanner, 2000).

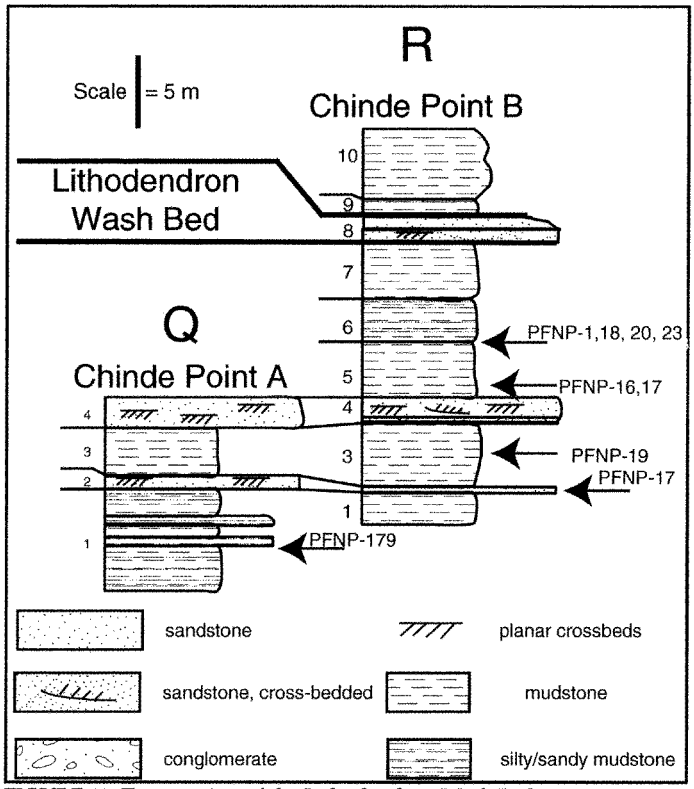

FIGURE 13. Type section of the Lithodendron Wash Bed.

LOCAL CORRELATION

Correlation within the PFNP (Figs. 4,6,7,9-11, 13) is accomplished by measured sections and tying together numerous laterally persistent bed-level units (Fig. 14). Within the Blue Mesa Member the only suitable such unit is the Newspaper Rock Bed (Fig. 4). The Newspaper Rock Bed has no correlatives in the park, but is easily traced laterally by either topographic expression or aerial photographs (Figs. 5B-D, 6). The Newspaper Rock Bed appears to be absent from the subsurface at the southern park headquarters based on the well data provided by Harrell and Eckel, 1938; Fig. 14). The Rainbow Forest Bed of the Sonsela Member is readily correlated across the Sonsela outcrop belt, and the Agate Bridge Bed is also useful for local and regional correlation.

Above the Sonsela Member, we accomplish local correlation in the PFNP using the Flattops 2-4 beds in the south (Figs. 10, 14) and the Lithodendron Wash and Black Forest beds in the north (Figs. 11, 14). The unit often identified as Flattops Bed 1 is an upper sheet of the Sonsela, specifically our Agate Bridge Bed, based on lithologic evidence documented here and by Espegren (1985). Other Flattops beds are readily traced across Painted Desert Member exposures in the southern half of the park and farther to the west (Billingsley, 1985b), but it is not yet certain how this and higher Flattops beds relate to bed-level units in the Painted Desert. The Lithodendron Wash Bed and Flattops Bed 2 are grossly similar. However, additional work will need to be completed before these sandstones can be convincingly correlated to each other (Figs. 14-15). Presently, the area in the vicinity of "Point of Bluff," "Two Buttes," and "Ramsey Slide" appears to be the best place to investigate these stratigraphic problems. The Black Forest Bed is the highest bed-level unit exposed in the PFNP and is strati-graphically higher than Flattops Sandstone 4 (Fig. 15).

Almost all of the correlations we advocate here have been proposed before, either in whole or in part (Figs. 3, 14). The most important thing we do here is provide a detailed database of measured sections documenting our stratigraphic hypotheses, and

Billingsley, 1985a	Ash, 1987a, 1992	This Paper	schematic lithologies
"Black Forest Tuff"	Black Forest Bed	Black Forest Bed	
"Painted Desert Ss 3"	"Painted Desert Ss 3"	Lithodendron Wash Bed	
"Painted Desert Ss 2"	"Painted Desert Ss 2"	unnamed (localized)	
"Painted Desert Ss 1"	"Painted Desert Ss 1"	Sonsela Member: Agate Bridge Bed	
		Sonsela Member: J.C. W. Bed	
Sonsela Ss Bed	Sonsela Ss Bed	Sonsela Member: Rainbow Forest Bed	

Roadifer, 1966	Billingsley, 1985a, b	This Paper	schematic lithologies
"Flattops Ss 3"	"Flattops Ss 4"	Flattops Bed 4	
"Flattops Ss 2"	"Flattops Ss 3"	Flattops Bed 3	
"Flattops Ss 1"	"Flattops Ss 2"	Flattops Bed 2	
"Flattops Bed 1"	"Flattops Ss 1"	Sonsela Member: Agate Bridge Bed	
"Camp Wash Zone"		Sonsela Member: Jim Camp Wash Bed	
Sonsela Ss Bed	Rainbow Sandstone	Sonsela Member: Rainbow Forest Bed	

FIGURE 14. Correlation of bed-level units of the Sonsela and Painted Desert members advocated here compared to historical usage. Top half is the northern portion of the park and bottom half is the southern half of the park.

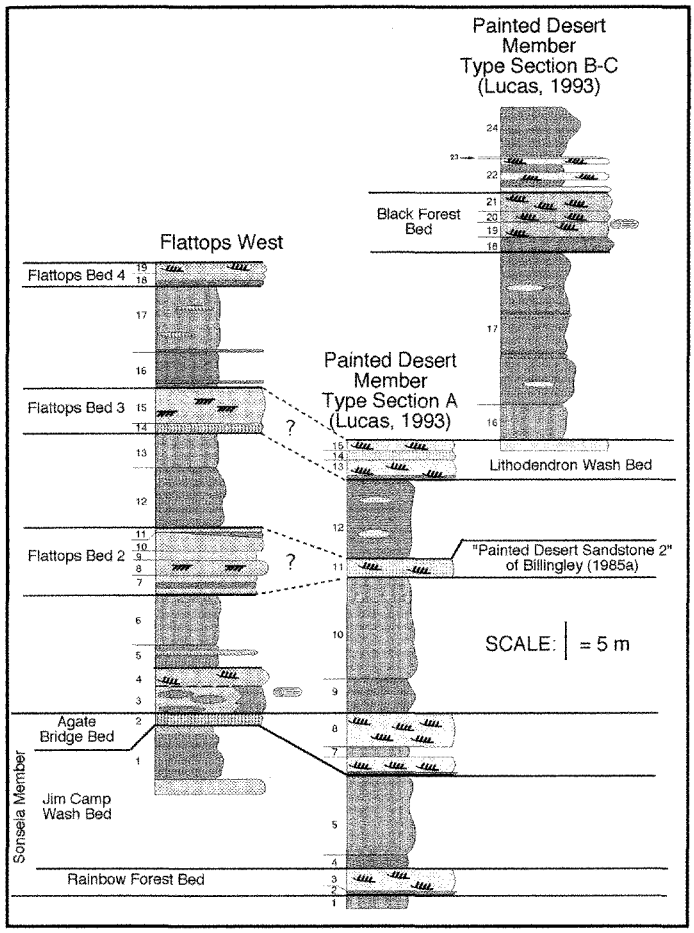

FIGURE 15. Tentative correlation of bed-level units in Painted Desert Member in the Petrified Forest National Park.

detailed descriptions of our measured sections (see Appendix). The other important aspect of this work is that we formalize many of the units used for correlation in the park, both by ourselves and by others. This can only improve our understanding of the stratigraphy of the park by clearly indicating what defines any given stratigraphic unit. The fact that all of these units have been mapped to some extent by Billingsley (1985b) also, in our view, justifies a useful, formal stratigraphy and indeed, most of the names used here for local correlation have been in use in some fashion for more than 40 years (Figs. 3, 14).

Subsurface Stratigraphy

No recent subsurface stratigraphic information is known from within the park, so we draw principally on water-well logs published by Harrell and Eckell (1939) to augment our discussion of the stratigraphy of PFNP. Two of these wells were spudded near the Rio Puerco at the railroad siding of Adamana outside the park, and a third was drilled at the southern park headquarters. These wells only penetrate Chinle Group strata, and we have discussed their importance in greater detail elsewhere (Heckert and Lucas, 1998b), so we will only briefly summarize the stratigraphic implications of these well records here.

The Adamana wells are situated approximately 10-15 m lower topographically than the lowest outcrops we report, namely the base of our Newspaper Rock section. These wells penetrated approximately 15 m of alluvium and fine-grained Chinle deposits before encountering sandstone and conglomerate we interpret as the Shinarump Formation. This indicates a total of at least 30 and perhaps 40 m of strata between the Shinarump Formation and the Blue Mesa Member of the Petrified Forest Formation, a figure consistent with typical regional thickness measurements of the Mesa Redondo Formation (Cooley, 1957; Stewart et al., 1972a). The well in the southern PFNP also indicates a minimum of 90 m of Chinle strata between the Shinarump Formation and the Sonsela Member, a figure consistent with a thick (70 m) Blue Mesa Member and thinner Bluewater Creek Formation or Mesa Redondo Formation. This conclusion supports our assertion that no Moenkopi Formation deposits crop out in the PFNP (Heckert and Lucas, 1998b) *contra* the interpretations of Dubiel et al. (1995, 1999) and Therrien et al. (1999).

REGIONAL CORRELATION

Strata of the PFNP are easily correlated to other Chinle outcrops on the Colorado Plateau. The base of the Chinle Group is not exposed within the boundaries of the park, although the subsurface information presented above indicates that as much as 35-40 m of fine-grained strata are present between the base of the Petrified Forest Formation and a coarse-grained unit that almost certainly represents the stratigraphically highest possible occurrence of the Shinarump Formation. We correlate strata at the base of our Newspaper Rock Bed type section, Lucas' (1993) type Blue Mesa Member section, and Cooley's PF-25 sections to the Bluewater Creek Formation (Fig. 4). Strata above this are assigned by us to the Petrified Forest Formation.

To further demonstrate this, we correlate strata within the park to the base of the Chinle section to the west (Fig. 16). A cursory look at large-scale geologic maps of the region surrounding PEFO (e.g., Reynolds, 1988; Kamilli and Richard, 1998) indicates that the Moenkopi-Chinle contact must lie between PEFO and the town of Holbrook, approximately 20 miles (32 km) to the west. Therefore, we investigated this issue by examining outcrops of the Chinle Group west of the southern entrance of the park. Here we observed several outcrops of lower Chinle Group strata and extrapolated our interpretations into the subsurface of the southern PEFO, where there is additional well control (Harrell and Eckel, 1938; Heckert and Lucas, 1998a).

Approximately 9.6 km WNW of the southern PEFO headquarters a series of low outcrops consists of (ascending) Moenkopi, "mottled strata," Shinarump, and Bluewater Creek formations. Just to the ESE and slightly higher topographically are outcrops of the Blue Mesa Member of the Petrified Forest Formation. All beds are essentially flat-lying. Moenkopi strata at point A (Fig. 16) consist of grayish red siltstones and sandstones. Overlying "mottled strata" are thin (1.5 m), limy to siliceous, pedogenically modified silt- and sandstones. Above the "mottled strata" are 1.6 m of well-indurated, trough-crossbedded, quartzose sandstones with pebble- to cobble-sized, siliceous conglomerate typical of the Shinarump Formation. At point B are greenish-gray and blue bentonitic mudstones typical of the lower Bluewater Creek Formation as described by Lucas and Hayden (1989) and Heckert and Lucas (1996). Outcrops between B and C are mostly covered, but at point C, bentonitic, pedoturbated mudstones and ash-rich silty sandstones typical of the Blue Mesa Member crop out, thus demonstrating the superposition of the Moenkopi, mottled strata, Shinarump, Bluewater Creek, and Petrified Forest Formations typical of these strata in western New Mexico (Lucas and Hayden, 1989; Heckert and Lucas, 1996, 2002).

The Petrified Forest Formation is remarkably consistent throughout the Colorado Plateau as a tripartite division of basal blue and purple bentonitic mudstones with minor light gray sandstones (Blue Mesa Member) a middle sandstone and conglomerate interval, (Sonsela Member) and an upper, less bentonitic redbed interval, (Painted Desert Member) (Stewart et al., 1972a; Lucas,

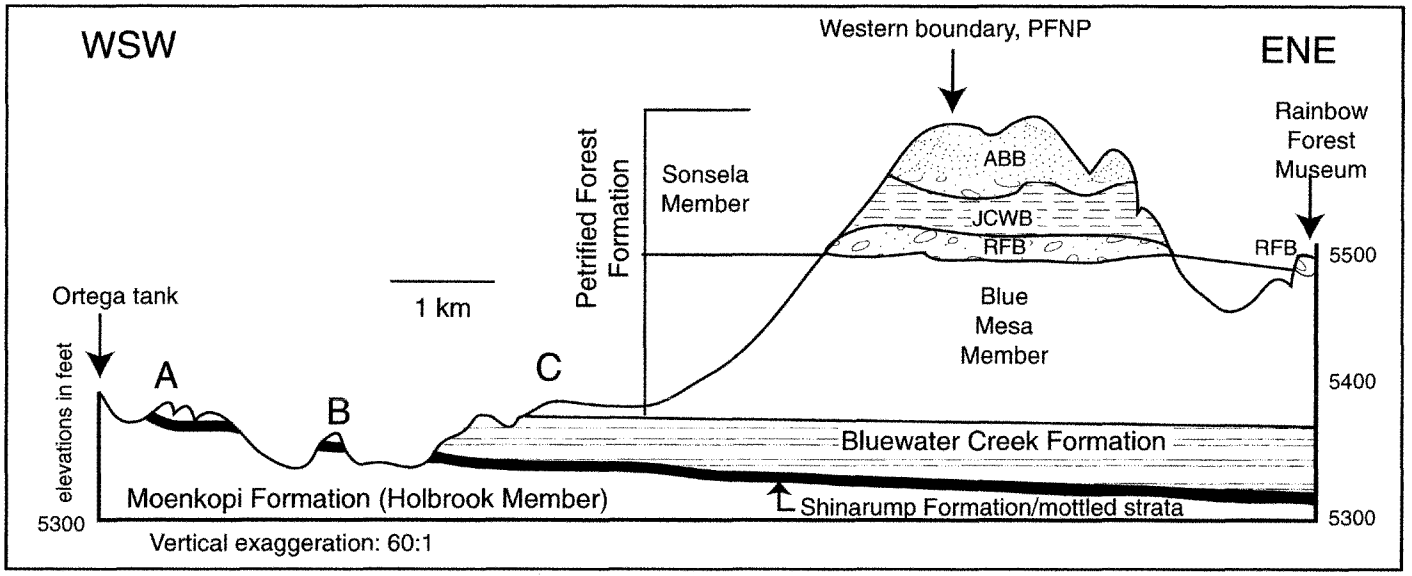

FIGURE 16. Figure showing the general relationships of Upper Triassic strata in the surface and near sub-surface of the southern Petrified Forest National Park. ABB = Agate Bridge Bed, JCWB = Jim Camp Wash Bed, RFB = Rainbow Forest Bed; all of the Sonsela Member.

1993; Lucas, 1997). This division has long been recognized, beginning with Gregory (1917), and these strata are easily correlated from the park to surrounding areas, although the nomenclature of these units varies across the Colorado Plateau (Lucas, 1993, 1997). The Painted Desert Member is also widespread, although correlation of bed-level units from the PFNP to other outcrop belts remains uncertain. Interbedded siltstones and pedogenic limestones of the Owl Rock Formation are easily recognized throughout the southern Colorado Plateau.

TETRAPOD BIOSTRATIGRAPHY AND BIOCHRONOLOGY

One of the principal motivating factors for this work was our desire to integrate the rich tetrapod fossil record of the park into a sound lithostratigraphic framework. Accordingly, we strove to identify the stratigraphic horizon of nearly 180 fossil localities plotted on a topographic map by Evanoff (1994). These localities include dozens of UCMP sites as well as localities excavated by the American Museum of Natural History (AMNH), the Smithsonian (USNM—United States National Museum), the Museum of Northern Arizona (MNA) and others (see Parker, 2002). Evanoff's (1994) compendium of PFNP-localities is similar to the PFV-localities Parker (2002) publishes in the following paper, but there may be some discrepancies, as Parker (2002) explains. All localities we plot here were field-checked and placed in the nearest measured section or, in some cases, required new measured sections. This paper is the first such database to match essentially all known vertebrate localities (through 1995) into detailed measured sections.

Two distinct vertebrate fossil assemblages have long been recognized in the PFNP: a late Carnian assemblage and a younger, Norian assemblage (Gregory, 1957; Colbert, 1972, 1985; Long, 1985; Long and Padian, 1986; Murry and Long, 1989; Murry, 1990; Lucas, 1993, 1995; Lucas and Hunt, 1993a,b; Hunt and Lucas, 1993a,b, 1995; Long and Murry, 1995). These assemblages were collected from narrow stratigraphic intervals below and above the Sonsela Member (Fig. 17; see also Figs. 4, 10, and 11). Other fossils from the PFNP used for biochronology include palynomorphs, megafossil plants, and calcareous microfossils (Ash, 1987; Lucas, 1993).

Gregory (1957) differentiated two vertebrate fossil assemblages in the PFNP but was unable to assign either to a stage within the Late Triassic, a position followed in later papers by Colbert (1972, 1985). Long (1985), Long and Padian (1986), Murry and Long (1989) and Long and Murry (1995) noted that a Norian vertebrate assemblage is present above the Sonsela, whereas a Carnian assemblage had been found below. Palynology (Litwin et al., 1991), plant megafossils (Ash, 1972b, 1980, 1987b), and calcareous microfossils (Kietzke, 1989; Lucas and Kietzke, 1993) indicate that the unconformity between the Sonsela and its correlatives and the underlying units approximates the Carnian-Norian boundary. Further biochronological studies by Lucas and Hunt (1993), Hunt and Lucas (1993a, 1995), and Lucas (1997, 1998) assigned these faunas to the Adamanian and Revueltian land-vertebrate faunachrons, of latest Carnian and early- to mid-Norian age, respectively.

The latest Carnian assemblage, collected in the Blue Mesa Member, consists mostly of the aetosaurs *Stagonolepis*, *Desmatosuchus* (=*Acaenasuchus*) and *Paratypothorax*, the phytosaur *Rutiodon* (=*Leptosuchus*), and abundant large metoposaurid amphibians of the genus *Buettneria* (Hunt and Lucas, 1993b), as well as many rarer reptilian taxa and diverse microvertebrates (Murry, 1989, 1990; Murry and Long, 1989; Long and Murry, 1995; Heckert, 2001). This assemblage was collected from a narrow stratigraphic interval in the Blue Mesa Member. Indeed, the collections from the vicinity of Blue Mesa (Camp, 1930; Long and Padian, 1986; Murry, 1989; Murry and Long, 1989; Long and Murry, 1995) form the basis of the Adamanian land-vertebrate faunachron (lvf) as defined by Lucas and Hunt (1993a) and Hunt and Lucas (1993a), and further modified by Lucas et al. (1997c) and Lucas (1998). The Adamanian is of latest Carnian (Tuvalian) age (Lucas, 1993, 1997, 1998).

Above the Sonsela Member, age-diagnostic vertebrate fossils include the aetosaur *Typothorax coccinarum*, the phytosaur *Pseudopalatus*, and abundant small metoposaurid amphibians of the genus *Apachesaurus* (Hunt and Lucas, 1993c; Long and Murry, 1995) and a new shark named elsewhere in this volume (Murry and Kirby, 2002). *Typothorax* and *Pseudopalatus* are index fossils of the Revueltian lvf, of Norian age (Hunt and Lucas, 1993a; Lucas and Hunt, 1993, Lucas, 1997, 1998). Abundant *Apachesaurus* are typical in Revueltian-aged rocks, whereas large metoposaurids (*Buettneria*) are relatively more abundant in Adamanian and older, Otischalkian, rocks, a relationship based in part on extensive fos-

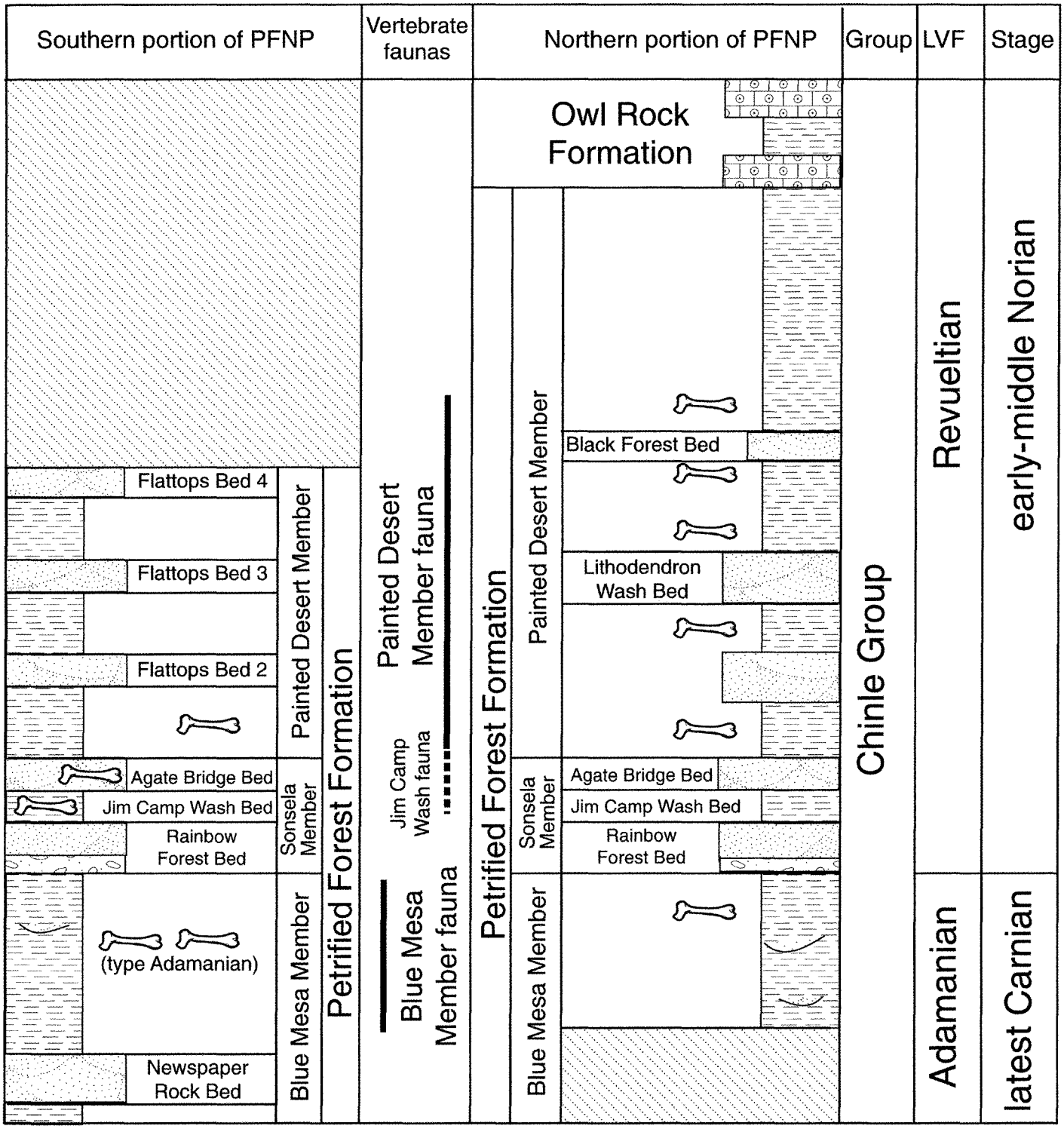

FIGURE 17. Tetrapod biostratigraphy and biochronology of Upper Triassic strata in the Petrified Forest National Park.

sil collecting in the PFNP (Hunt and Lucas, 1993c). With our revised interpretation of the stratigraphy in the southern part of the park, it is now clear that there is a tetrapod fauna from the Jim Camp Wash and Agate Bridge beds of the Sonsela (see also Hunt et al., 2002), which we refer to as the "Jim Camp Wash fauna" in Figure 17. Based on descriptions in Long and Murry (1995) cross-referenced with the localities identified here (Evanoff, 1994) and by Parker (2002), this fauna includes the phytosaur *Pseudopalatus*, the aetosaur *Typothorax*, and metoposaurid amphibians, indicating a Revueltian (early-mid Norian) age. It is possible that a few typical Adamanian taxa (the phytosaur *Rutiodon* and the aetosaur *Stagonolepis*) occur very low in this interval, but we have not been able to confirm Long and Murry's (1995) identications and cross-reference them to the localities plotted here, principally in Figure 4. Accordingly, the Jim Camp Wash appears to represent earliest Revueltian time, based on tefirst occurrences of *Pseudopalatus* and *Typothorax coccinarum*.

Hunt and Lucas (1993a, 1995), Hunt (1993, 1994), Lucas (1995) and Heckert and Lucas (1998c) recognize two vertebrate fossil assemblages from the Painted Desert Member and its cor-

relatives in the western United States. The first of these faunas exists lower in the section and contains a diverse aetosaur assemblage of *Desmatosuchus*, *Paratypothorax*, *Aetosaurus*, and *Typothorax* and is correlative to the typical Revueltian fauna of Hunt and Lucas (1993a). The upper fauna is less diverse, with only two aetosaurs, *Typothorax coccinarum* and *Aetosaurus*, carrying over from the earlier Revueltian (Small, 1998; Heckert and Lucas, 1998c), but adding a new species of *Desmatosuchus* (see Zeigler et al., 2002), and represents a distinct subset of Revueltian time, although the stratigraphic range of *Aetosaurus* in the Chinle Group is not well-constrained, and *Aetosaurus* records from outside the U.S. indicate that it probably survived into the late Norian or even Rhaetian (Heckert and Lucas, 2000). Careful correlation of fossil localities within the park may allow separation of these two intervals and biostratigraphic correlation of sandstone beds within the Painted Desert Member. Unfortunately, all known vertebrate fossil localities in the Painted Desert Member occur relatively low in the section; almost all are below the Black Forest Bed. This makes further biostratigraphic subdivision here unlikely.

Recently, Hunt (2001) followed earlier suggestions that the Revueltian lvf could (should) be subdivided (e.g., Hunt and Lucas, 1993a; Lucas, 1997) and proposed three sub-lvfs for Revueltian time (ascending order): Rainbowforestan (RO), Barrancan (R1) and Lucianoan (R2). He based the Rainbowforestan on the vertebrate fauna of the Sonsela Member (Jim Camp Wash and Agate Bridge beds of our usage) of the Petrified Forest Formation in the vicinity of the Rainbow Forest. Hunt (2001) defined the Rainbowforestan lvf as the time between the first appearance datum (FAD) of *Nicrosaurus* and the (later) FAD of *Pseudopalatus*. However, as Hunt et al. (2002) in this volume indicates, we believe the phytosaur specimen from the Sonsela Member that Hunt assigns to *Nicrosaurus* should be identified as *Pseudopalatus*. This taxonomic reassignment thus undermines the definition of Rainbowforestan time proposed by Hunt (2001). Furthermore, the skull in question comes from the Agate Bridge Bed of the Sonsela Member, and thus lies very close to the first occurrence of other *Pseudopalatus* specimens throughout the PFNP and elsewhere, which are low in the Painted Desert Member. As a consequence, we do not recognize a distinct interval of Rainbowforestan time versus the Barrancan, which is essentially the type Revueltian. Future collecting, particularly in the vicinity of Jim Camp Wash, may yet bear out Hunt's (2001) hypothesis, but until such time as a distinct index fossil or other FAD can be used to identify Rainbowforestan time, we cannot recognize any substantive difference between the Rainbowforestan and Barrancan lvfs.

Hunt's (2001) Barrancan sub-lvf is based on the type assemblage of the Revueltian lvf as originally proposed by Lucas and Hunt (1993a). Hunt defined the Barrancan as the time between the FAD of *Pseudopalatus* (which is the end of his Rainbowforestan) and the FAD of the ornithischian dinosaur *Lucianosaurus*, which is the beginning of Lucianoan time. However, despite the regional utility of the ornithischian dinosaurs *Tecovasaurus* and *Revueltosaurus* in Chinle Group correlations (Heckert and Lucas, 1997; Heckert, 2001, 2002), *Lucianosaurus* remains a rare taxon, known only from the type locality in eastern New Mexico. Because of its rarity, we believe the FAD of *Lucianosaurus* is not well established, nor are we able to identify this FAD with confidence outside of east-central New Mexico. Thus, using it to define the beginning of a biochronological unit is not convincing, as Hunt (2001) conceded.

We thus conclude that the biochronological subdivision of the Revueltian lvf advocated by Hunt (2001) is weakly supported. Like Hunt (2001), we think that Revueltian time is relatively long and amenable to subdivision. However, the biostratigraphic basis for a convincing subdivision remains elusive, and will require further collecting. At present, Revueltian time remains a single, tetrapod-based biochronological unit encompassing most, if not all, of early-middle Norian time.

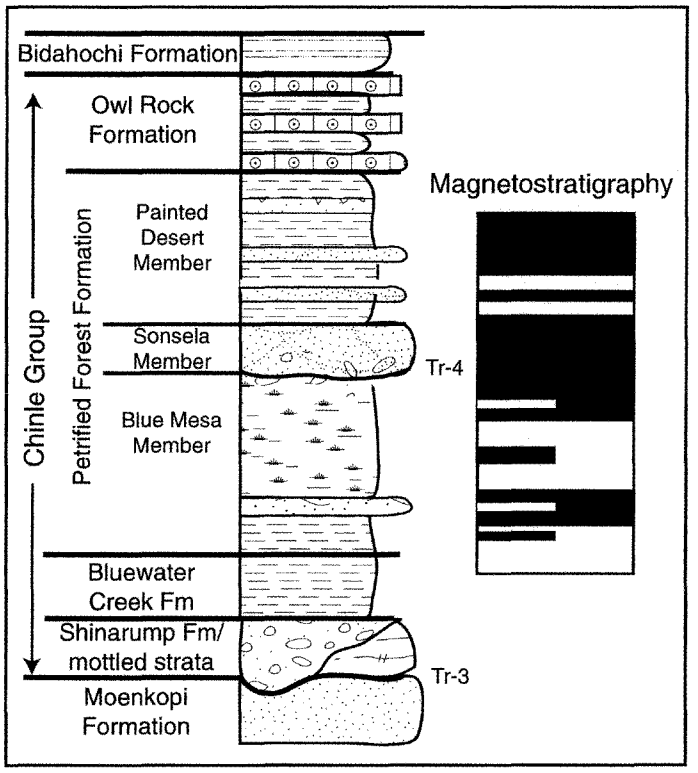

FIGURE 18. Generalized magnetostratigraphy of the Petrified Forest National Park according to Steiner and Lucas (2000).

The Owl Rock Formation in the PFNP has not received the paleontologic scrutiny accorded to lower units. However, vertebrate fossil collections from this unit elsewhere, particularly those reported by Kirby (1989, 1990, 1991, 1993), demonstrate that the Owl Rock Formation is also of Revueltian (Norian) age, based on the occurrence of a typical Revueltian fauna including *Typothorax coccinarum* and *Pseudopalatus* (Lucas and Hunt, 1993a; Lucas, 1997).

MAGNETIC AND ISOTOPE CHRONOLOGY

Steiner and Lucas (2000) published a magnetostratigraphy for the stratigraphic interval of the Blue Mesa Member, Sonsela Member, and lower part of the Painted Desert Member (up to and including the Black Forest Bed) at the PFNP (Fig. 18). The very base of their section is in what we now identify as the Bluewater Creek Formation. There are several polarity reversals recorded in this stratigraphic interval, and Steiner and Lucas (2000) correlated this magnetostratigraphy to the Newark Supergroup magnetostratigraphy of Kent et al. (1995) by placing the Carnian-Norian boundary at the base of the Sonsela Member. This correlation (Steiner and Lucas, 2000, fig. 9) appears reasonable but is not unambiguous based solely on matching magnetostratigraphy. Indeed, an equally plausible correlation based solely on matching magnetostratigraphy would correlate the entire PFNP Chinle magnetostratigraphy to the early Norian portion of the Newark Supergroup. We conclude, therefore, that the PEFO magnetostratigraphy presented by Steiner and Lucas (2000) only weakly supports existing correlation of the Chinle to the Newark based on biostratigraphy. Indeed, the strong correlation of the PFNP magnetostratigraphy to lithotype (Steiner and Lucas, 2000) is also troubling and may indicate that the magnetostratigraphic record they document is not completely reliable.

Two numerical ages have been reported from the PFNP, both from the Black Forest Bed. Ash (1992) suggested that a K-Ar age on biotite of 239±9 Ma is the age of a Middle Triassic tuff that was subsequently reworked during Late Triassic time to form the Black Forest Bed. Riggs et al. (1994a) reported a U-PB age on zircons from the Black Forest Bed of 207±2 Ma and suggested it is the syndepositional age of the unit. Riggs et al. (1994b) went further to conclude that the Black Forest Bed represents the fluvial deposition of a Plinian ash fall that disrupted stream flow causing avulsion and crevasse splay formation.

This sedimentological interpretation seems unlikely because: (1) the tuff of the Black Forest Bed is extremely localized, which would not be the case in a Plinian ash fall; and (2) geometry and sedimentary structures of the Black Forest Bed differ little from those of the Painted Desert Member channel deposits, which suggests an ash fall was not needed to produce this type of facies architecture. Furthermore, an age of 207 Ma for the early Norian Black Forest Bed seems unlikely, unless all previous calibration of the Late Triassic timescale is incorrect (Lucas, 1994b). Therefore, neither of the published numerical ages of the Black Forest Bed reliably calibrates the early Norian. Presently we are working with another laboratory to date zircons from the Black Forest tuff using U-Pb methods. Preliminary dates from this analysis are much more consistent with an biochronological and lithostratigraphic constraints on the age of the Black Forest Tuff (J. Mortensen, written comm., 2002).

CONCLUSIONS

Triassic strata exposed in the PFNP belong to three distinct formations, the Bluewater Creek, Petrified Forest and Owl Rock Formations. The stratigraphically lowest of these, the Bluewater Creek Formation, crops out at the base of mudstone-dominated slopes in the vicinity of Newspaper Rock, the Teepees, and the Haystacks. Above the Bluewater Creek Formation the basal Petrified Forest Formation is represented by the mudstone-dominated Blue Mesa Member, which is locally as much as 77.7 m thick. We have formalized the term Newspaper Rock Bed to facilitate correlation of strata within the park. Almost all vertebrate localities within the Blue Mesa Member at PFNP are found in a narrow stratigraphic interval well above the Newspaper Rock Bed and below the Sonsela Member.

The Blue Mesa Member is disconformably overlain by the Sonsela Member, a crossbedded conglomerate and conglomeratic sandstone that locally contains abundant petrified wood. The base of the Sonsela marks an unconformity, the Tr-4 unconformity of Lucas (1993). As at the type section (Akers et al., 1958; Lucas et al., 1997b), the Sonsela consists of upper and lower coarse-grained units separated by a finer-grained interval. We formalize these units here as the Rainbow Forest, Jim Camp Wash, and Agate Bridge beds. Consequently, we identify a much thicker (up to ~40 m) Sonsela section at PFNP than do previous workers.

Uppermost Sonsela strata grade upward into mudstones and sandstones of the Painted Desert Member, which is approximately 147.2 m thick within the park. In the vicinity of the Flattops, sandstones in the Painted Desert Member are named Flattops Beds 2-4 (ascending). Flattops Bed 2 is the most areally extensive of the Flattops beds and overlies a number of vertebrate localities. This unit may be equivalent to, or at least homotaxial with, the Lithodendron Wash Bed in the southern Painted Desert. Flattops beds 3 and 4 also resemble the Lithodendron Wash Bed in the Painted Desert, but are limited in areal extent due to Quaternary erosion.

The Owl Rock Formation is exposed along the northern edge of the PFNP, where it consists of up to 30.6 m of interbedded siliciclastics and pisolitic limestones. Although locally unfossiliferous, fossils from Owl Rock Formation strata elsewhere constrain the age of the uppermost Chinle sediments in the PFNP to the Revueltian (early-middle Norian).

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APPENDIX 1—LOCATIONS OF MEASURED STRATIGRAPHIC SECTIONS

The following table lists locations of measured sections in Arizona used for this report. Sections identified with a PFNP were measured by us at localities with that designation described by Evanoff (1994); sections are credited to other authors as appropriate. Measured sections with no credit were measured as part of this project. Detailed descriptions of measured sections are available in the following places: new type units in Appendix 2, other sections we measured in Appendix 3, others in the original citation.

#	Name (and author)	Location(s)
1	Giant Logs	N1/2 SW1/4 SW1/4 to NW1/4 NW1/4 SW1/4 sec. 35, T17N R23E
2	Highway 260N/PFNP-14 (Roadifer, 1966)	SW 1/4 sec. 35, T17N, R23E
3	Cooley's (1957) Rainbow Forest	W1/2 S1/2 NW1/2 to W1/2 N1/2 NW1/2 sec. 1, T16N R23E
4	PFNP-6 (Roadifer, 1966): Antelope Petroglyph	SE 1/4 SW 1/4 sec. 36, T17N, R23E to NW1/4 NE1/4 SW1/4 sec. 36 T17N R23E
5	Long Logs	NE1/4 NE1/4 SE1/4 sec. 1, T16N, R23E
6	New Pipeline Road	NW1/4 NE1/4 NW1/4 sec. 20, T17N R24E
7	PFNP-7 (Roadifer, 1966)	NW1/4 NW1/4 sec. 20, T17N, R24E
8	PFNP-7A (Roadifer, 1966)	NW1/4 NE1/4 sec. 20, T17N, R24E
9	Hill 5573	Units 1-4 along the edge of SW and NW 1/4 sec. 16, 5-7 in NE1/4 SW1/4 SW1/4 sec. 16, 8-13 on the south side of hill with benchmark 5573 in SE1/4 NE1/4 SE1/4 sec. 17; T17N R24E
10	Martha's Butte West—Hill 5650	SW1/4 NW1/4 NE1/4 sec. 20, T17N R24E
11	Crystal Forest	SW1/4 NE1/4 NW1/4 sec. 22 T17N R24E
12	Jasper Forest West (PFNP-11 of Roadifer, 1966)	NE 1/4 NE 1/4 sec. 1, T17N, R23E
13	Jasper Forest (PFNP-10 of Roadifer, 1966)	NE1/4 NW 1/4 sec. 7, T17N, R24E
14	Jasper Forest (Murry and Long, 1989)	sec. 8, T17N, R24E (34° 53' 5"N, 109° 48' 29"W)
15	Agate Bridge W/PFNP-5 (Roadifer, 1966)	SE 1/4 NW 1/4 sec. 4, T17N, R24E
16	Sonsela Section (Murry and Long, 1989)	SE1/4 SE1/4 sec. 4, T17N, R24E
17	PFNP-12 (Roadifer, 1966)	NW 1/4 SW 1/4 sec. 11, T17N, R24E
18	PFNP-9, PFNP-9A (Roadifer, 1966)	SE1/4 SE 1/4 sec. 22, T18N, R24E and SW 1/4 SW 1/4 sec. 23, T18N, R24E
19	Type Blue Mesa Member A (Lucas, 1993)	SW1/4 SW1/4 SE1/4 sec. 21, T18N, R24E
20	Type Blue Mesa Member B (Lucas, 1993)	SW1/4 NW1/4 SW1/4 NE1/4 sec. 22, T18N R24E
21	Type Blue Mesa Member C (Lucas, 1993)	SE1/4 NW1/4 SW1/4 sec. 23, T18N, R24E
22	Type Blue Mesa Member D (Lucas, 1993)	E1/2 SE1/4 SE1/4 SW1/4 sec. 23, T18N, R24E
23	Camp's Butte (Murry and Long, 1989)	E1/2 SE1/4 SE1/4 SW1/4 sec. 23, T18N, R24E
24	PFNP-2 (Roadifer, 1966)	SW 1/4 NW 1/4 sec. 25, T18N, R24E
25	PFNP-15 (Roadifer, 1966)	SE 1/4 sec. 24, T18N, R24E
26	PFNP-16 (Roadifer, 1966)	NW 1/4 sec. 30, T18N, R25E
27	PFNP-4 (Roadifer, 1966)	NE 1/4 NE 1/4 sec. 21 T18N, R24E
28	Newspaper Rock Section (PF 25, Cooley, 1957)	SE1/4 SE1/4 NW1/4 sec. 6 T18N R24E
29	Newspaper Rock Bed Type Section	SE1/4 SE1/4 NW1/4 sec. 6 T18N R24E
30	PFNP-3 (Roadifer, 1966)	SW 1/4 SE 1/4 sec. 9, T18N, R24E
31	Wizard Wash	SE1/4, SW1/4 NE1/4 sec. 15, T19N, R23E
A	West Butte/PFNP-13 (Roadifer, 1966)	SE1/4 sec. 25, T17N, R23E
B	New Pipeline Road	NW1/4 NE1/4 NW1/4 sec. 20, T17N R24E
C	Bluffs West of Battleship (PFNP-7a of Roadifer, 1966)	NW 1/4 NW 1/4 sec. 20, T17N, R24E
D	Bluffs West of Battleship (PFNP-7 of Roadifer, 1966)	NW1/4 NE1/4 sec. 20, T17N, R24E
E	Flattops West	SW1/4 SE1/4 sec. 30, T18N, R24E and NW1/4 SW1/4 NW1/4 to SW1/4 NE1/4 NW1/4 sec. 32, T17N R24E
F	SMU Flattops (from Murry and Long, 1989)	sec. 32, T17N, R24E (34° 49' 50"N, 109° 48' 49"W)
G	Cooley's (1957) Flattops (PF-23A)	S1/2 SE & SW1/4, sec. 32, T17N, R24E
H	PFNP-4 (Flattops of Roadifer, 1966)	SE 1/4 SW 1/4 sec. 32, T17N, R24E
I	East Water Tank (PFNP-16 of Roadifer, 1966)	NW 1/4 sec. 30, T18N, R25E
J	PFNP-8A & PFNP-8B (Roadifer, 1966)	SW1/4 SE1/4 sec. 23 and NE 1/4 NE 1/4 sec. 13, T19N, R23E
K	Type Painted Desert Member A (Lucas, 1993)	SE1/4 NE1/4 sec. 11, T19N, R23E
L	Petroglyph Butte	SW1/4 NE1/4 SE1/4 sec. 13, T19N, R23E
M	PFNP-8C (Roadifer, 1966)	NE1/4 NW 1/4 sec. 17, T19N, R24E
N	PFNP 40	SW1/4 SW1/4 SE1/4 sec. 18, T19N, R24E
O	Dinosaur Hill 2	sec. 18, T19N R24E (35°, 2' 46"N, 109° 49' 47")
P	SMU Lungfish Localities (Murry, 1989)	sec. 18, T19N, R24E (35°, 3' 7"N, 109° 50' 10")
Q	Chinde Point A	NE1/4 NW1/4 NE1/4 sec. 33 (unsurveyed), T20N, R24E
R	Chinde Point B	NW1/4 SE1/4 NE1/4 sec. 33 (unsurveyed), T20N, R24E
S	TType Painted Desert Member B (Lucas, 1993)	W1/2 NW1/4 SW1/4 sec. 34 (unsurveyed), T20N, R24E
T	Type Painted Desert Member C (Lucas, 1993)	NW 1/4 sec. 9 and SW 1/4 sec. 4 (unsurveyed), T20N, R24E
U	Type Black Forest Bed (Ash, 1992)	SW1/4 SW1/4 SW1/4 sec. 33 (unsurveyed), T20N, R24E
V	PFNP-10	NE1/4, SW1/4 NE1/4 sec. 34 (unsurveyed), T20N, R24E
W	Cooley's (1957) PF-24	SW1/4 sec. 34 (unsurveyed), T20N, R24E
X	Painted Desert Inn (Cooley's PF-24A)	SW1/4 sec. 34 (unsurveyed), T20N, R24E
Y	Black Forest	NE1/4 NE1/4 sec. 28 (unsurveyed), T20N, R24E
Z	PFNP-8	NW1/4 NW1/4 NW1/4 sec. 35 (unsurveyed), T20N, R24E

APPENDIX 2: TYPE SECTIONS OF BED-LEVEL UNITS

The following are type sections for bed-level stratigraphic units formalized in this paper. These include the Newspaper Rock Bed of the Blue Mesa Member, the Rainbow Forest, Jim Camp Wash, and Agate Bridge beds of the Sonsela Member, and Flattops Beds 2-4 and the Lithodendron Wash Bed of the Painted Desert Member. Colors are those of Goddard et al. (1984).

Newspaper Rock Bed Type Section

Section measured in the SE1/4 SE1/4 NW1/4 sec. 6 T18N R24E. Strata considered flat-lying. Section measured by A.B. Heckert and C. Davis.

unit **lithology** **thickness (m)**

Chinle Group:
Petrified Forest Formation:
Blue Mesa Member:
Newspaper Rock Bed:

12 Sandstone; pale greenish yellow (10Y8/2) to light greenish gray (5GY8/1) fresh, weathers/stains to grayish orange pink (5YR7/2) and light brown (5YR6/4); very fine-grained, subangular to subrounded, micaceous quartzarenite; ripple laminated; weathers into large (up to 4-5 m) blocks at edge of plateau; not calcareous; top is undulose stripped surface mantled with Recent deposits; cliff-former. 3.1-4.0

11 Sandstone; light greenish gray (5GY8/1) fresh; weathers to dark yellowish brown (10YR4/2); very fine- to fine-grained, subrounded, moderately well-sorted, micaceous quartzarenite; blocky to flaggy; interbedded with sandstones of unit 10 lithology; not calcareous; cliff-former. 2.1

10 Sandstone; mostly grayish yellow green (5GY7/2) fresh with darker and lighter shades common; weathers to grayish orange (10YR7/4) ; very fine-grained, subangular to subrounded, well-sorted, very micaceous quartzarenite; ripple laminated; subject to blowouts and forms a notched cliff. 1.4

9 Sandstone; light greenish gray (5GY8/1) fresh; weathers to a desert varnish that is light brown (5Y6/4) to dark yellowish brown (10YR4/2); fine-grained, subrounded to subangular, well-sorted, micaceous dirty quartzarenite/sublitharenite; ripple laminated; base scours into underlying unit as much as 0.5 m locally; not calcareous; forms the base of a cliff composed of the Newspaper Rock Bed. 1.2

Thickness of Newspaper Rock Bed: 8.7 m

Blue Mesa Member (lower part):

8 Bentonitic mudstone bleach-out; predominantly light greenish gray (5GY8/1) with specks/mottles of dark yellowish orange (10YR6/6); popcorn weathering; slightly slickensided; not calcareous. 0.7

7 Bentonitic mudstone; moderate light gray (N6) to light gray (N7); forms a slope; not calcareous. 1.3

6 Bentonitic mudstone; pale red purple (5RP6/2) with some very light gray (N8) mottling; not calcareous. 1.1

5 Bentonitic mudstone; grayish blue (5PB5/2); some popcorn weathering on slopes; forms a prominent dark band. 10.5

4 Bentonitic mudstone; grayish red purple (5RP4/2); not calcareous. 1.5

3 Ashy/muddy sandstone and sandy mudstone; tuffaceous; light gray (N7) to very light gray (N8); fine- to medium-grained, subangular to subrounded, moderately poorly sorted, very micaceous lithic wackestone to litharenite; micas are both muscovite and biotite, possibly some phlogopite; calcareous; forms smooth but hard, well-indurated slopes. 4.6

Thickness of lower beds of Blue Mesa Member: 19.6 m
Thickness of incomplete Blue Mesa Member: 28.3 m

Bluewater Creek Formation:

2 Bentonitic mudstone; pale purple (5P6/2); very slightly silty; not calcareous. 0.5-0.6

1 Bentonitic mudstone; grayish red purple (5RP4/2) with mottles of light greenish gray (5GY8/1); some micas; not calcareous.2.0+

Thickness of incomplete Bluewater Creek Formation: 2.6 m+

Giant Logs

(Type Section of Rainbow Forest, Jim Camp Wash, and Agate Bridge beds)

Section measured from the N1/2 SW1/4 SW1/4 to NW 1/4 NW1/4 SW1/4 section 35, T17N R23E, Apache County, Arizona. Strata are flat-lying. Section measured by S.G. Lucas and field assistants.

unit **lithology** **thickness (m)**

Chinle Group:
Petrified Forest Formation:
Sonsela Member:
Agate Bridge Bed:

15 Sandstone; pinkish gray (5YR8/1) and light greenish gray (5G8/1);very fine- to fine-grained, subrounded, moderately well-sorted quartzarenite; clay pebble floaters; trough crossbedded; top is a stripped surface; not calcareous. 1.5++

14 Sandstone and conglomerate; moderate yellowish brown (10YR5/4) and yellowish gray (5Y7/2); fine- to medium-grained, subrounded, moderately well-sorted quartzarenite; some feldspars and biotite; trough crossbedded; some clay ball and siltstone floaters as conglomeratic stringers; not calcareous. 1.1

13 Sandstone; yellowish gray (5Y7/2); fine- to medium-grained, subrounded, well-sorted quartzarenite; some biotites; laminar to planar crossbedded; not calcareous. 1.1

12 Sandstone; yellowish gray (5Y8/1) fresh, weathers moderate yellowish brown (10YR5/4); very fine- to medium-grained, subrounded, poorly sorted, subarkose; much biotite; trough crossbedded; unit contains some petrified wood; slightly calcareous; forms a cliff. 1.9

11 Sandstone and limestone pebble conglomerate; light olive gray (5Y6/1) and yellowish gray (5Y8/1) with brownish black (5YR2/1) specks; fine- to very coarse-grained, subangular to subrounded; poorly sorted quartzarenite; some feldspars; trough crossbedded; much scour-and-fill at base of unit. 0.75-1.0

Thickness of Agate Bridge Bed: 6.6m+

Jim Camp Wash Bed:

10 Sandy claystone and sandstone; light greenish gray (5GY8/1) with flecks of biotite that are brownish black (5YR2/1); sand is very fine-grained, subangular quartzarenite; blocky; not calcareous. 3.25

9 Bentonitic mudstone; grayish purple (5P4/2) and very dusky red purple (5RP2/2) mottled pale greenish yellow (10Y8/2); numerous pale olive (10Y6/2) to pale greenish yellow (10Y8/2) calcrete nodules; stacked paleosols; not calcareous. 7.25

8 Bentonitic mudstone; same colors and lithology as unit 5. 3.0

7 Sandstone; banded light brownish gray (5YR6/1) and brown-ish black (5YR2/1); fine-grained, subrounded to subangular, well-sorted micaceous subarkose; trough crossbedded; some limestone cobble conglomerate; not calcareous. Locally this unit produces abundant unionid bivalves. 2.1

6 Bentonitic mudstone; grayish red purple (5RP4/2) with olive gray (5Y4/1) to light greenish gray (5GY8/1) calcrete nodules; paleosol; calcareous. 1.5

5 Bentonitic mudstone; pale red (5R6/2) and grayish red (10R4/2) with mottles of light greenish gray (5GY8/1); slightly calcareous. 4.5

4 Sandstone; yellowish gray (5Y8/1) with olive black (5Y2/1) specks; contains much altered ash; fine-grained, subangular to subrounded, well-sorted, clayey very micaceous sandstone; same lithology as Crystal Forest unit 6; laminar; calcareous. 2.8

3 Bentonitic mudstone; same lithology as unit 1 but more very light gray (N8) coloration; trough crossbeds. 5.5

Thickness of Jim Camp Wash Bed: 29.9 m

Rainbow Forest Bed:

2 Conglomeratic sandstone; white (N9) to pinkish gray (5YR8/1) with light gray (N7) clay balls; coarse- to very-coarse grained, moderately well-sorted, subangular quartzarenite; conglomeratic clasts are bentonitic clay balls and quartzite pebbles up to 3 cm in diameter; also much jasper, chert; trough crossbedded; much petrified wood (Giant Logs); not calcareous. 2.25

Thickness of Rainbow Forest Bed: 2.25 m

Thickness of Sonsela Member: 38.75+ m

unconformity (Tr-4 unconformity of Lucas, 1993)

Blue Mesa Member:

1 Bentonitic mudstone; grayish purple (5P4/2) with very light gray (N8) mottles; slightly silty; not calcareous. 1.75+

Thickness of incomplete Blue Mesa Member: 1.75 m+

Flattops west

(Type section of Flattops beds 2-4)

Section measured in the SW1/4 SW1/4 SW1/4 sec. 30 to 5662 benchmark (units 1-11) and the NW1/4 SW1/4 NW1/4 to SW1/4 NE1/4 NW1/4 section 32 (units 12-19), all in T17N R24E. Section measured by S.G. Lucas and field assistants.

unit lithology thickness (m)

Chinle Group:

Petrified Forest Formation:

Painted Desert Member:

Flattops Bed 4:

19 Sandstone; pale red (5R6/2), pinkish gray (5YR8/1) and light gray (N7); same lithology as unit 18; trough-crossbedded; soft-sediment deformation; massively bedded as in unit 15A. 1.6+

18 Intraformational conglomerate and sandstone; sandstone is pale red (5R6/2) to grayish red (5R4/2), very fine- to fine-grained, subrounded, well-sorted, micaceous quartzarenite; calcareous; conglomerate is same colors with clay pebbles like unit 17 up to 3 mm in diameter; matrix is a coarse chert sand; unit is trough- and planar crossbedded; calcareous. 1.8

Thickness of Flattops Bed 4: 3.4+ m

mudstone interval:

17 Bentonitic mudstone; pale red (5R6/2) to grayish red (10R4/2); silty to sandy; calcareous; thin sandstone lenses of very fine-grained, subrounded well-sorted quartzarenites; and conglomerates with chert and limestone pebbles. 8.75

16 Bentonitic mudstone; grayish red (10R4/2) with pale greenish yellow (10Y8/2) mottles; slightly sandy; not calcareous; unit contains nodular calcrete horizons which are light olive gray (5Y5/2) and yellowish gray (5Y7/2); calcareous; two conglomerates present that are brownish black (5YR2/1) and brownish gray (5YR4/1) pebbles of limestone, mudstone, and quartzite up to 50 mm in diameter; calcareous; conglomerates are near base and at top; upper conglomerate produces unionid bivalves. 4.75

Flattops Bed 3:

15 Sandstone; yellowish gray (5Y8/1) and brownish gray (5YR4/1); very fine- to fine-grained, subrounded, well-sorted sublitharenite; calcareous; planar bedding to planar crossbeds, with some massive coarse beds, especially at top (15A); calcareous. 4.9

14 Conglomeratic sandstone; olive gray (5Y4/1) to yellowish gray (5Y8/1); pebbles are limestone and chert up to 50 mm in diameter; matrix is very fine- to coarse-grained, subangular, poorly sorted quartzarenite; some jasper and chert; graded bedding; some trough scouring; mostly planar or planar crossbedded; calcareous. 1.3

Thickness of Flattops Bed 3: 6.2+ m

mudstone interval:

13 Sandy mudstone; light greenish gray (5GY8/1) and yellowish gray (5Y8/1); sands are very fine-grained quartz and jasper; some carbonaceous plant debris; slightly calcareous. 4.5

12 Bentonitic mudstone; grayish red purple (5RP4/2) and grayish red (5R4/2); slightly calcareous. 8.0

Flattops Bed 2:

11 Sandstone; same colors and lithology as unit 9; basal conglomerate has limestone and siltstone pebbles up to 1.5 cm in diameter; same colors as sandstone; laminar; tops bench; channels into unit 10 as much as another 0.75 m. 0.75

10 Sandstone; light olive gray (5Y6/1) and light brownish gray (5YR6/1); fine- to medium-grained, subrounded, well-sorted; mineralogy like unit 9; not calcareous; bioturbated; blocky to pillowy. 2.6

9 Sandstone; brownish gray (5YR4/1) to light brownish gray (5YR6/1); very fine-grained, subrounded, well-sorted arenite with quartz, chert, jasper, feldspars, and biotites; laminar; forms a slope; not calcareous. 1.25

8 Sandstone; brownish gray (5YR4/1) to light brownish gray (5YR6/1); very fine- to fine-grained, subrounded, well-sorted quartzarenite to sublitharenite; micaceous; planar crossbedded; not calcareous; cliff-former. 2.0

7 Sandstone and limestone conglomerate; bleached-out unit is yellowish gray (5Y8/1); sandstone is very fine- to fine-grained, subrounded to rounded, moderately well-sorted micaceous sublitharenite; some carbonaceous debris; conglomerate is chert-pebble conglomerate with calcite cement; sandstone matrix like rest of unit; medium gray (N4) chert pebbles up to 50 mm; calcareous. 2.25

Thickness of Flattops Bed 2: 8.85 m

mudstone interval:

6 Bentonitic mudstone; grayish red purple (5RP4/2) to light brownish gray (5YR6/1); silty; calcareous; break in slope. 6.75

5 Bentonitic claystone; pale red (5R6/2) and grayish red purple (5RP4/2) with pale greenish yellow (10Y8/2) mottles; swirls and stripes; unit is blocky and hackly fresh; slightly calcareous. 3.0

Sonsela Member:

Agate Bridge Bed:

4 Sandstone; pinkish gray (5YR8/1), yellowish gray (5Y8/1) and greenish gray (5GY6/1); medium- to coarse-grained, subangular to subrounded, poorly to moderately poorly sorted sublitharenite; some feldspars, chert, jaspers, and biotites; heterolithic; softer portions of unit 3 lithology; some silica-pebble conglomerates; trough crossbedded; not calcareous; forms a persistent bench. 2.5

3 Sandstone and conglomerate; sandstone is greenish gray (5GY6/1) and yellowish gray (5Y8/1), fine- to medium-grained, subangular to subrounded, moderately well-sorted quartzarenite; clayey; much bioturbation; trough crossbedded; some post-diagenetic gypsum in clumps; about 2 m above base are lenses of bentonitic mudstone that are light olive gray (5Y6/1) and slightly calcareous. 3.8

2 Sandstone; pinkish gray (5YR8/1) and yellowish gray (5Y8/1); very fine- to medium-grained, poorly sorted, subangular micaceous subarkose; conglomeratic in places with medium dark gray (N4) quartzite pebbles up to 25 mm in diameter; some carbonized petrified wood is brownish black

(5YR2/1); calcareous. 1.8
Thickness of Agate Bridge Bed: 8.1 m

Jim Camp Wash Bed:

1 Bentonitic mudstone; yellowish gray (5Y8/1); calcareous. not measured

Lithodendron Wash Bed type section

Section measured in the NW1/4 SE1/4 NE1/4 sec. 33, T20N R24E by A.B. Heckert and C. Davis.

unit **lithology** **thickness (m)**

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:

10 Bentonitic mudstone; pale reddish brown (10R5/4); steep slope. This unit = unit 16 of the type Painted Desert Member of Lucas (1993). not measured

Lithodendron Wash Bed:

9 Sandstone; grades into sandy mudstone that is identical to unit 10 but slightly silty/sandy; sandstone is pale red (10R6/2) and pale greenish yellow (10Y8/2); very fine- to fine-grained, subangular to subrounded, moderately well-sorted sublitharenite; more poorly indurated/slope forming than unit 8 below; unit pinches and swells with unit 8; not calcareous. 1.5+

8 Sandstone; pale greenish yellow (10Y8/2) with pale red (10R6/2) bands fresh; weathers grayish red (10R4/2) and brownish gray (10YR4/1); fine-grained, subrounded, moderately well-sorted sublitharenite; crossbedded; ripple laminated top; weakly calcareous; forms a prominent ledge; thicker to west. 1.0
Thickness of Lithodendron Wash Bed: 2.5 m

mudstone interval:

7 Bentonitic mudstone; pale red purple (5RP6/2); not calcareous. 4.0

6 Bentonitic mudstone; pale reddish brown (10R5/4) with some olive gray (5Y4/1) calcrete nodules; popcorn weathering; not calcareous. 3.0

5 Bentonitic mudstone; pale red (10R6/2) and pale greenish yellow (10Y8/2); not calcareous. 4.0

4 Sandstone; pale red (10R6/2) and light greenish gray (5GY 8/1); fine-grained, subrounded, moderately well-sorted slightly micaceous dirty sublitharenite; much planar- and trough-crossbedding; not calcareous; forms prominent bench mantled with remnants of unit 5; basal conglomerate is calcrete-nodule rip-up with clasts up to 10 mm; clast-supported, and 0.2-0.5 m thick; channels into unit 3 up to 0.3 m; very calcareous. 1.75

3 Bentonitic mudstone; pale red (5R6/2) and pale greenish yellow (10Y8/2); calcareous. 4.25

Sonsela Member:
Agate Bridge Bed:

2 Sandstone and conglomerate; forms a ripple-laminated ledgy break in slope; brownish gray (5YR4/1); sandstone is medium-grained, subrounded, moderately well-sorted sublitharenite; conglomerate is a calcrete-pebble conglomerate with clasts up to 30-40 mm in long axis, most 2-4 mm diameter; very well-indurated; highly calcareous; locally bone-bearing. 0.2

1 Bentonitic mudstone; pale reddish brown (10R5/4) and darker; produces some unionids; not calcareous. 2.0+

APPENDIX 3—LITHOLOGIC DESCRIPTIONS OF MEASURED SECTIONS, PETRIFIED FOREST NATIONAL PARK AND VICINITY, NAVAJO AND APACHE COUNTIES, ARIZONA

Wizard Wash

Section measured in the SE1/4, SW1/4 NE1/4 sec. 15, T19N, R23E. Strata are flat-lying. Section measured by A.B. Heckert and C. Davis.

unit **lithology** **thickness (m)**

Chinle Group:
Petrified Forest Formation:
Sonsela Member:

4 Sandstone; pinkish gray (5YR8/1) fresh, weathers light gray (N7); fine- to coarse-grained, subangular to subrounded, poorly sorted muddy, dirty quartzarenite; some thin conglomeratic stringers; trough crossbeds; some purple mudstone interbeds; not calcareous. 3.0+

3 Sandy mudstone and very muddy conglomeratic sandstone; mudstone is white (N9) and pale blue (5PB7/2); not calcareous; sandstone is fine- to medium grained, subangular to subrounded lithic wacke; white (N9) with clasts of chert/jasper and quartzite up to 25 mm in long axis that are grayish red (5R4/2) and moderate yellowish brown (10 YR5/4) among other colors; trough cross-bedded; friable; sandstone crops out as thin ledge. 1.5

unconformity (Tr-4 unconformity of Lucas, 1993)

Blue Mesa Member:

2 Bentonitic mudstone; pale purple (5P4/2) to grayish purple (5P6/2); paleosol; many white (N9) to light greenish gray (5GY8/1) root casts visible in fresh outcrops; popcorn weathering; not calcareous. 2.3

1 Muddy sandstone; yellowish gray (5Y8/1) with minor pale purple (5P6/2); very fine- to fine-grained, subrounded to rounded, well-sorted muddy micaceous quartzarenite; floors "Wizard Wash" and "Fossil Garden" and is very fossiliferous; some conglomeratic stringers; much biotite with jasper up to 10-15 mm in diameter; bentonitic mudstone interbeds; not calcareous. 3.0

Antelope Petroglyph

Section measured in the NW1/4 NE1/4 SW1/4 sec. 36, T17N R23E and begins at the top of Roadifer's (1966) unpublished PFNP-6. Strata are flat-lying. Section measured by A.B. Heckert and C. Davis.

unit **lithology** **thickness (m)**

Chinle Group:
Petrified Forest Formation:
Sonsela Member:

5 Sandstone; pinkish gray (5YR8/1) with whitish spots fresh, weathers to pale red (5R6/2) and light brownish gray (5YR6/1); fine-grained, subrounded, moderately well-sorted, micaceous, muddy sublitharenite; ripple laminated to flaggy; forms a stripped surface. 1.7+

4 Sandstone; same colors and lithology as units 1 and 3; more massive; forms a small cliff. 0.8

3 Sandstone; same colors and lithology as unit 1. 0.75

2 Sandy/silty bentonitic mudstone; light brownish gray (5YR6/1); calcareous; forms a much-covered slope. 3.1

1 Sandstone; light brownish gray (5YR6/1); fine- to very fine-grained, subangular to subrounded, moderately well-sorted, micaceous, sublitharenite; similar to unit 11 and Roadifer's (1966) PFNP-6, but laminar to sheety; forms more of a slope; not calcareous. 1.6
Thickness of incomplete Sonsela Member: 7.9 m+

Long Logs

Section measured in the NE1/4 NE1/4 SE1/4 sec. 1, T16N, R23E, Apache County, Arizona. Strata are flat-lying. Section measured by A.B. Heckert and C. Davis.

unit	lithology	thickness (m)
Chinle Group:		
Petrified Forest Formation:		
Blue Mesa Member:		
5A	Bentonitic mudstone; medium gray (N5); calcrete nodules of similar colors; calcareous.	1.0+
5	Sandstone; yellowish gray (5Y8/1), weathers to light brownish gray (5YR6/1); medium- to coarse-grained, subangular, moderately well-sorted sublitharenite; some conglomeratic lenses with many calcrete nodules 10-12 mm in diameter; low angle trough crossbeds; forms thin ledges; weathers into 0.5 m-sized, spheroidal blocks; base is not calcareous except calcrete clasts.	3.0
4	Sandstone and pebble conglomerate; yellowish gray (5Y8/1) and light brownish gray (5YR6/1); sandstone is medium-grained, subrounded, moderately-well sorted, muddy sublitharenite; conglomerate is calcrete nodule pebble conglomerate with clasts averaging 3-4 mm in diameter; very poorly indurated except for one laminar to ripple-laminated ledge; some low angle trough crossbeds on fresh surfaces; not calcareous.	2.0
3	Bentonitic mudstone; pale red purple (5RP6/2) with mottles of yellowish gray (5Y8/1); some light brown (5YR5/6) pith/root casts in band 0.4 m thick 3.6 m above base; not calcareous; popcorn weathering; forms a steep slope.	6.0
2	Silty bentonitic mudstone; same colors as 3; above; not calcareous.	0.9
1	Sandstone; yellowish gray (5Y8/1) with pale purple (5P6/2) mottling; fine-grained, subrounded, moderately well-sorted, muddy sublitharenite; jasper pebble conglomerate in places; abundant petrified wood; "Long Logs" unit.	2.0+
	Thickness of incomplete Blue Mesa Member: 14.9 m+	

Martha's Butte North—Hill 5650

Section measured in the SW1/4 NW1/4 NE1/4 sec. 20, T17N R24E on a bluff with a prominent 5650 foot contour approximately 1.5 miles west of the Battleship and almost due north of Martha's Butte. Strata are flat-lying. Section measured by A.B. Heckert and C. Davis.

unit	lithology	thickness (m)
Chinle Group:		
Petrified Forest Formation:		
Sonsela Member:		
Agate Bridge Bed:		
9	Conglomerate and conglomeratic sandstone; grayish yellow (5Y8/4) with pale rep purple (5RP6/2) spots; sandstone and matrix is coarse- to medium-grained, subangular, moderately well-sorted sublitharenite; muddy; calcareous; top is a stripped surface; forms a prominent crest; this unit = unit 11 of Roadifer's (1966) PFNP-6 section.	not measured
8	Conglomerate; clasts are grayish yellow (5Y8/4), light olive gray (5Y5/2), medium dark gray (N4) and moderate brown (5YR4/4); clasts consist primarily of chert pebbles up to 40 mm in diameter.	2.5+
Jim Camp Wash Bed:		
7	Bentonitic mudstone and sandstone; mudstone is light olive gray (5Y6/10 and medium light gray (N4) with grayish red (5R4/2) nodules; basal 1.0 m thick sandstone is same colors; sandstone is fine- to medium-grained, subangular, moderately well-sorted, muddy sublitharenite; friable; a log is present in the sandstone lags; mudstone and nodules are calcareous; sandstone is not.	7.2
6	Muddy, bentonitic siltstone and silty, bentonitic mudstone; pale red (5R6/2); not calcareous.	3.3
5	Heterolithic unit; top is a conglomerate and conglomeratic sandstone; very light gray (N8) to light gray (N7) with moderate orange pink (10R7/4) specks/mottles; medium-coarse grained, subangular, moderately well-sorted; poorly indurated; some crossbeds; mostly a slope former with many rounded ledges; base is a light olive gray (5Y6/1) siltstone; not calcareous.	4.5
4	Bentonitic mudstone; Identical to unit 9 of Hill 5573 section: pale red purple (5RP6/2) with flecks of yellowish gray (5Y7/2); slightly silty; not calcareous.	4.0
3	Ashy, powdery sandstone; light greenish gray (5GY8/1); fine-grained, subrounded, moderately well-sorted sublitharenite; some jasper and chert pebbles; not calcareous. May be equivalent to Long Logs or Rainbow Forest Sandstone.	2.5
2	Bentonitic mudstone; identical to unit 6 of Hill 5573 section: pale red purple (5P6/2) to red purple (5P4/2) with light greenish gray (5GY8/1) mottles/flecks.	1.1
1	Bentonitic mudstone; pale brown (5YR5/2) with flecks of pale greenish yellow (10Y8/2); not calcareous.	not measured
	Thickness of incomplete Jim Camp Wash Bed: 22.6m	

Hill 5573

Section measured in several fragments, 1-2 and 3-4 along the boundary between SW and NW 1/4 sec. 16, 5-7 in NE1/4 SW1/4 SW1/4 sec. 16, and 8-13 on the south slope of hill with elevation mark 5573 in the SE1/4 NE1/4 SE1/4 sec. 17, all in T17N R24E. Strata are flat-lying. Section measured by A.B. Heckert and C. Davis.

unit	lithology	thickness (m)
Chinle Group:		
Petrified Forest Formation:		
Sonsela Member:		
Agate Bridge Bed(?):		
13	Agatized conglomerate; moderate reddish orange (10R6/6) to moderate reddish brown (10R4/6) and pale purple (5P6/2) clasts;, former are heavily agatized with pinkish gray (5YR8/1) matrix; forms a thin but very resistant ledge; not calcareous; stripped surface on top of hill 5573.	1.0+
Jim Camp Wash Bed:		
12	Mudstone; same color and lithology as unit 9.	4.0
11	Siltstone; light greenish gray (5G8/1); not calcareous.	1.0
10	Sandstone/wacke; pale red (5R6/2) with pale greenish yellow (10Y8/2) flecks; fine- to medium-grained, subrounded, micaceous lithic wacke; not calcareous.	2.7
9	Bentonitic mudstone; pale red purple (5PR6/2) with flecks of yellowish gray (5Y7/2); slightly silty; not calcareous.	1.4
8	Bentonitic mudstone; light olive gray (5Y6/1); not calcareous.	1.4
7	Mudstones; interbedded lithologies like units 8 and 9.	3.3
6	Bentonitic mudstone; pale red purple (5P6/2) to red purple (5P4/2) with light greenish gray (5GY8/1) mottles/flecks.	1.25
	Thickness of Jim Camp Wash Bed: 16.1 m	
Rainbow Forest Bed:		
5	Conglomerate and sandstone; yellowish gray (5Y8/1) to pinkish gray (5YR8/1); sandstone and sandstone matrix is medium- to coarse-grained, subangular, moderately poorly sorted, muddy sublitharenite; not calcareous; clasts are mudstone rip-us and reworked calcrete nodules; well-indurated; much scour and fill; forms a prominent ledge with a stripped upper surface northeast of hill 5573.	2.7
4	Intraformational conglomerate; grayish blue (5PB5/2) to pale pink (5RP8/2); intraformational with calcrete nodules and mudstone rip-up clasts; not calcareous.	0.5

3 Sandy/silty mudstone; grayish purple. 1.5-2.0
2 Sandstone and conglomeratic sandstone; clasts up to 5 cm in diameter; micaceous; forms a low ridge; much wood at base and/or in lower unit/
Thickness of Rainbow Forest Bed: 5.2m+
unconformity (Tr-4 unconformity of Lucas, 1993)
Blue Mesa Member:
1 Bentonitic mudstone; red purple (5RP4/2) to purple (5P4/2). 1.0+

Agate Bridge West

Section measured almost exactly where Roadifer measured his PFNP-5 section, about 0.5 miles west of park road at and above locality PFNP-162 in the SE 1/4 NW 1/4 sec. 4, T17N, R24E. Strata are flat-lying. Section measured 14 July 1995 by A.B. Heckert and C. Davis.

unit **lithology** **thickness (m)**
Chinle Group:
Petrified Forest Formation:
Sonsela Member:
Agate Bridge Bed:
6 Sandstone; yellowish gray (5Y8/1) to pinkish gray (5Y8/1), with some bands of medium dark gray (N4) to dark gray (N3); very fine- to coarse-grained, rounded, very poorly sorted quartzarenite; ashy and clayey; some mudstone rip-up clasts; micaceous; friable; laminar and trough cross-bedded; degree of induration and weathering highly variable laterally; not calcareous; forms a weathered cliff. 8.0+
5 Conglomerate; clasts of quartzite, chert, and jasper, of highly variable colors, including reds, oranges, browns, and grays; clast-supported; well-rounded; clasts up to 50 mm in diameter common, others larger; matrix is white (N9) with some light greenish gray (5G8/1); weakly cemented; not calcareous. 2.3
4B Sandstone, grading upward into siltstone; sandstone is yellowish gray (5Y8/1) and light gray (N7); fine- to medium-grained, subrounded, moderately well-sorted clayey/ashy micaceous sublitharenite; siltstone is light greenish gray (5GY8/1) to grayish yellow green (5GY7/2); slightly sandy; micaceous; bentonitic; not calcareous. 6.3
4A Conglomerate; clasts of chert and quartzite; shades of brown, gray, and grayish purple; clasts up to 10 cm long axis; subrounded to rounded; matrix is medium- to very coarse-grained, subrounded, poorly sorted sublitharenite; very friable; not calcareous. 0.5
Thickness of Agate Bridge Bed: 18.1 m+
Jim Camp Wash Bed(?):
3A Bentonitic mudstone; yellowish gray (5GY8/1); not calcareous. 0.3
3 Bentonitic mudstone; grayish red purple (5RP4/2); some light greenish gray (5GY8/1) spots, most less than 1-2 mm in diameter; some lighter bands visible; not calcareous; forms a bright purple band that is very striking from road. 9.1
Thickness of Jim Camp Wash Bed: 9.4 m
Rainbow Forest Bed(?):
2 Sandstone; white (N9) to light greenish gray (5GY8/1) and minor pale blue (5PB7/2); many grayish blue (5PB5/2) to grayish purple (5P4/2) mudstone rip-ups; medium-grained, subangular to subrounded, moderately well-sorted, clayey litharenite with rip-ups up to 20 mm in diameter; higher unit is mottled light greenish gray (5GY8/1) and pale purple (5P6/2) with a prominent purple band 2.5 m above base; sandstone is fine-grained, subangular to subrounded, moderately well-sorted, slightly clayey litharenite; not calcareous; basal conglomeratic lag is fossiliferous with isolated bones and teeth; some petrified wood locally; may be the Rainbow Forest Bed. 6.0
Thickness of Rainbow Forest Bed: 6.0 m
unconformity (Tr-4 unconformity of Lucas, 1993)
Blue Mesa Member:
1 Fossiliferous interval; bentonitic mudstone; grayish blue (5PB5/2) and grayish purple (5P4/2); some spots of yellowish gray (5Y8/1); not calcareous; this is the horizon of PFNP-162 and correlates with PFNP-161, which is in a bentonitic mudstone that is grayish blue (5PB5/2) with some yellowish gray (5Y8/1) mottles, slightly silty, and not calcareous. PFNP-161 crops out significantly closer to the road in a low flat/blow-out that faces west. 4.5+

Crystal Forest

Section measured approximately .75 miles (1.25 km) east of the Crystal Forest trail head in the SW1/4 NE1/4 NW1/4 sec. 22 T17N R24E. This section was published previously but not described in detail by Lucas and Hunt (1992). Strata are flat-lying. Section measured by A.B. Heckert and C. Davis.

unit **lithology** **thickness (m)**
Chinle Group:
Petrified Forest Formation:
Painted Desert Member:
7 Siltstone; purple and blue; forms a prominent marker bed. 0.5-07
Sonsela Member:
Agate Bridge Bed:
6 Sandstone; pinkish gray (5YR8/1) with brownish black (5YR2/1) specks; weathers yellowish gray (5Y8/1); very fine- to fine-grained, subrounded, well-sorted quartzarenite; not calcareous; interbedded with sandy siltstone is pale red purple (5RP6/2) to grayish red purple (5RP4/2); not calcareous; forms thin ledges; heavily bioturbated; trough cross-bedded. 3.0
5 Interbedded sandy claystone and clayey sandstone; claystone is light brownish gray (5YR6/1) with mottles of very light gray (N8); not calcareous; sandstone is pinkish gray (5YR8/1) and yellowish gray (5Y8/1); very fine- to fine-grained, subrounded to subangular, micaceous quartzarenite to subarkose; not calcareous. 1.1
4 Clayey sandstone and silty claystone; sandstone is grayish red purple (5RP4/2) and light brownish gray (5YR6/1); very fine-grained, subangular micaceous quartzarenite; some dark minerals; not calcareous; some green bands; fossil bone at base of unit; claystone is pale olive (10Y6/2); not calcareous. 1.5
3 Sandy claystone; light greenish gray (5GY8/1) with minor dark greenish gray (5G4/1); altered tuff with biotite flecks; not calcareous; siliceous sands; trough crossbedded; not calcareous. 0.5
2 Slightly sandy claystone; grayish red purple (5RP4/2) with very light gray (N8) mottles; heterolithic but contains more clay than unit 1; trough crossbedded; not calcareous. 1.8
1 Clayey sandstone; grayish pink (5R8/2) and greenish gray (5G6/1) with light brownish gray (5YR6/1) claystone chips; fine- to medium-grained, subangular to subrounded, poorly sorted quartzarenite; green and gray trough crossbeds; base of unit contains abundant, jasperized petrified logs; not calcareous; *Paratypothorax* locality at top of unit. 4.25
Thickness of exposed Sonsela Member: 12.15 m

New Pipeline Road

Section measured in the NW1/4 NE1/4 NW1/4 sec. 20 T17N R24E across a road not on the Agate House 1:24000 map. Strata considered flat-lying.

unit **lithology** **thickness (m)**
Chinle Group:

Petrified Forest Formation:
Painted Desert Member:
Flattops Bed 2:

5 Sandstone; pale brown (5YR5/2); fine- to medium-grained, subangular, slightly muddy sublitharenite and light brownish gray (5YR6/1); medium-grained, subrounded moder ately poorly sorted muddy sublitharenite; slightly calcareous contains a muddy interval consisting of a muddy, fine- to medium-grained; moderately well-sorted, calcareous quartzarenite. 3.0+

mudstone interval:

4 Bentonitic mudstone; color intermediate between pale purple (5P6/2) and grayish purple (5P4/2) with light greenish gray (5GY8/1) spots; very calcareous. 12.0

"Flattops Bed 1":

3 Ashy sandstone; white (N9) to very light gray (N8); very fine- to coarse-grained, subangular, muddy, micaceous (biotite) quartzarenite; calcareous; a prominent purple band, consisting of a 0.25-0.5 m thick, calcareous pale red (5R6/2) silty to sandy bentonitic mudstone with light greenish gray (5GY8/1) flecks and spots is present 3.5 m above the base of this unit. 5.3

mudstone interval:

2 Sandy bentonitic mudstone; pale purple (5P6/2) to grayish blue (5PB5/2); calcareous; a lensy sand halfway up channels into this unit and, in 1/4 1/4, etc. all the way down into unit 1; this sandstone is very light gray (N8), tending to light greenish gray (5G8/1) and is a subrounded, moderately well-sorted, fine-grained quartzarenite; not calcareous. 3.0

Sonsela Member:
Agate Bridge Bed:

1 Sandstone; light olive gray (5Y6/1) to greenish gray (5GY6/1); fine- to coarse-grained, poorly sorted, subangular, muddy sublitharenite; this unit equals unit 11 of Roadifer's PFNP-6 section, and forms an excellent marker bed; forms plateau top/ roadbed. 2.0+

PFNP-8

Section measured in the vicinity of locality PFNP-8 (Evanoff, 1994—PFV 8 of Parker, 2002) by A.B Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:
Lithodendron Wash Bed:

5 Sandstone; same colors and lithology as unit 3; low angle planar crossbeds. 1.5+

4 Sandstone; grayish red (10R4/2) with pale greenish yellow (10Y8/2) spots; fine-grained, subrounded, micaceous litharenite; much covered by colluvium; calcareous. 1.5

3 Sandstone; moderate reddish orange (10R6/6) and yellowish gray (4Y8/1); fine-grained, subrounded, well-sorted sublitharenite; low-angle planar crossbeds; scours into unit 2 in places; not calcareous; ledgy. 0.75-1.0

Thickness of Lithodendron Wash Bed: 4.0 m+

mudstone interval:

2 Mudstone; paler red (10R6/2) with mottles and flecks of light greenish gray (5GY8/1); not calcareous. 3.8

1 Intraformational conglomerate; moderate red (5R5/4) to pale yellowish brown (10YR6/2) and olive black (5Y2/1); very poorly indurated, with most clasts being calcrete pebbles; this horizon produces numerous unionids locally along with occasional vertebrate teeth. 1.5+

PFNP-40—Dinosaur Hill

Section measured in the SW1/4 SW1/4 SE1/4 sec. 18, T19N, R24E, near "Dinosaur Hill" (see Parker, 2002, for the complex history of "Dinosaur Hill"). Section measured by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:

4 Bentonitic mudstone; pale reddish brown (10R5/4) with light greenish (5GY8/1) spots; very waxy; very slightly silty; light olive gray (10Y6/1) calcrete nodules; not calcareous. 2.25+

3 Bentonitic mudstone; pale red purple (5RP6/2); some flecks/spots of light greenish gray (5GY8/1); very fossiliferous, especially at top; not calcareous. 2.9

2 Bentonitic mudstone; grayish orange pink (5YR7/2) and pale yellowish brown (10YR6/2) with halos of light greenish gray (5GY8/1) around grayish blue (5PB5/2) spots up to 30 mm in diameter; replaced laterally to west by unit 1 lithologies; not calcareous. 3.8

Lithodendron Wash Bed:

1 Sandstone; light gray (N7) fresh, weathers to pale reddish brown (10R5/4); fine- to medium-grained, subangular to subrounded, moderately well-sorted sublitharenite; also a calcrete pebble conglomerate; very coarse-grained litharenite that is greenish gray (5GY6/1) to dark greenish gray (5GY4/1); crossbedded; soft sediment deformations; weathers to hoods and ledgy slopes; only conglomerate is calcareous; floors arroyo on north side of PFNP-40. 3.5+

Mid-Painted Desert Section (Hill 5528)

Section measured on an isolated mesa in the SE1/4 SE1/4 SE1/4 sec. 1, T19N, R21E. Unit 16 of the type Painted Desert Member overlies unit 8 of this section. Section measured by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:
Lithodendron Wash Bed:

8 Sandstone; white (N9) to light greenish gray (5GY8/1); fresh with pale blue (5PB7/2) bands fresh; weathers to moderate reddish orange (10R6/6) and pale reddish brown (10R5/4); fine- to medium-grained subangular to subrounded; moderately well-sorted sublitharenite; planar crossbedded appearing as red and green stripes in outcrop; caps mesa; calcareous. 3.0+

7 Conglomerate; light greenish gray (5GY8/1) and grayish blue (5PB5/2) fresh, weathers to pale red (10R6/2); calcrete pebbles 4-6 mm in diameter; coarse sand matrix; calcareous. 0.5

Painted Desert Member:

6 Bentonitic mudstone; identical to unit 5 except with numerous thin ledges of conglomerate and/or sandstone; conglomerate is pale red (10R6/2) with some light greenish gray (5GY8/1); calcrete pebble and mudstone rip-ups 2-4 mm in diameter; most sands are same colors, very coarse-grained litharenites; calcareous; form numerous "ribs" in lower third to half of this unit; forms a very sheer; crumbly slope. 15.0

5 Bentonitic mudstone; pale red (10R6/2); many calcrete nodules; calcareous. 20.75

4 Bentonitic mudstone; mottled grayish purple (5P4/2) and light gray (N7); popcorn weathering; many calcrete nodules; forms a gradual slope. 1.5

3 Bentonitic mudstone; yellowish gray (5Y8/1) and very light gray (N8); numerous dark yellowish brown (10YR4/2) siderite/calcrete nodules; micaceous; popcorn weathering; calcareous; slope-forming unit. 2.2

Sonsela Member:
Agate Bridge Bed(?):

2 Sandstone; grayish orange pink (5YR7/2) with some pale greenish yellow (5GY7/2) mudstone interbeds; fine- to medium-grained, subangular to subrounded, moderately poorly sorted (bimodal) sublitharenite; unit is heterolithic where measured but more uniform and cliffy due west; conglomeratic at base with numerous calcrete rip-ups up to 15 mm in diameter; planar crossbeds dip to north; forms a ribbed, steep slope. 2.3

Jim Camp Wash Bed?:

1 Bentonitic mudstone; pale red (10R6/2); many light greenish gray (5GY8/1) spots and some nodules; calcareous. 2.0

Petroglyph Butte

Section measured on west face of butte immediately to the northeast of the topographic feature informally known as "Petroglyph Mesa" in the SW1/4 NE1/4 SE1/4 sec. 13, T19N R23E by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:
Lithodendron Wash Bed:

8 Sandstone and conglomerate; sandstone is predominantly light greenish gray (5GY8/1) fresh, weathering to pale reddish brown (10R5/4); fine- to medium-grained, subrounded, moderately well-sorted sublitharenites and dirty quartzarenite; low- to medium- angle planar crossbeds; well-indurated for 3.3 m, then becomes more mud-dominated, less well-indurated; calcareous; thin conglomerates are intraformational with 2-4 mm calcrete nodules, very well-indurated; unit is calcareous. 7.0+

7 Intraformational conglomerate/lithic sandstone; medium light gray (N6) and white (N9) fresh; very coarse-grained sandstone to conglomerate; subangular to angular, moderately well-sorted conglomeratic litharenite; lensy; clasts are calcrete pebbles and mudstone rip-ups; calcareous. 0.6

Thickness of Lithodendron Wash Bed: 7.6 m+

mudstone interval:

6 Bentonitic mudstone; pale reddish brown (10R5/4) to moderate brown (5YR4/4); forms a steep, popcorn-weathering slope; calcareous. 18.5

5 Mudstone and sandstone interbedded as unit 4 grades into 5; mudstones like unit 3; sandstones are light greenish gray (5GY8/1) fresh, weathers to moderate orange pink (10R7/4); very fine- to fine-grained; subrounded to subangular; moderately poorly sorted sublitharenite; weakly calcareous. 2.5

4 Sandstone; light gray (N7) to medium light-gray (N6) fresh; weathers light brownish gray (5YR6/1); fine- to medium-grained, subrounded to subangular, moderately well-sorted sublitharenite; ledgy; base is planar crossbedded; calcareous; forms a ledgy slope to rounded cliff. 4.0

3 Bentonitic mudstone; pale red purple (5RP6/2); popcorn weathering; calcareous. 7.0

2 Bentonitic mudstone; yellowish gray (5Y8/1); upper 0.5 m stained by unit 3; produces some bone from a thin, poorly indurated conglomerate; calcareous. 5.2

1 Bentonitic mudstone; grayish red (10R4/2); calcareous; abundant calcrete nodules; produces some bone (PFNP-41) approximately 2 m from top; floors arroyo. not measured

Chinde Point I

Section measured on an isolated butte at the junction of the Chinde-Kachina point drainage and Lithodendron Wash in the NE1/4 NW1/4 NE1/4 sec. 33, T20N, R24E by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:

4 Sandstone; brilliant bands of pale reddish brown (10R5/4) and yellowish gray (5Y8/1) to light greenish gray (5GY8/1); fine-grained, subangular to subrounded, micaceous sublitharenite; many well-preserved planar crossbeds in sets 0.2-0.5 m thick; occasional calcrete pebble conglomerates; not calcareous; this unit = unit 4 of Chinde Point II section. 2.0+

3 Bentonitic mudstone; pale red (10R6/2); blocky; very few reduction spots; not calcareous. 3.3

2 Sandstone; pale reddish brown (10R5/4); very fine- to fine-grained, subangular, micaceous; dirty sublitharenite; some crossbedding; hoodooish weathering pattern; lensy; not present above PFNP-179 across wash; weakly calcareous. 1.0

1 Silty mudstone; mottled pale reddish brown (10R5/4) or a little darker and light olive gray (5Y6/1); fossiliferous, producing some fossil bone on southeast side of butte; calcareous; first unit out of wash. 7.25+

Chinde Point II

(Lithodendron Wash Bed Type Section)

Section measured in the NW1/4 SE1/4 NE1/4 sec. 33, T20N R24E, by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:

10 Bentonitic mudstone; pale reddish brown (10R5/4); steep slope. not measured

Lithodendron Wash Bed:

9 Sandstone; grades into sandy mudstone that is identical to unit 10 but slightly silty/sandy; sandstone is pale red (10R 6/2) and pale greenish yellow (10Y8/2); very fine- to fine-grained, subangular to subrounded, moderately well-sorted sublitharenite; more poorly indurated/slope forming than unit 8, below; unit pinches and swells with unit 8; not calcareous. 1.5+

8 Sandstone; pale greenish yellow (10Y8/2) with pale red (10R6/2) bands fresh; weathers grayish red (10R4/2) and brownish gray (10YR4/1); fine-grained, subrounded, moderately well-sorted sublitharenite; crossbedded; ripple laminated top; weakly calcareous; forms a prominent ledge; thicker to west. 1.0

Thickness of Lithodendron Wash Bed: 2.5 m+

mudstone interval:

7 Bentonitic mudstone; pale red purple (5RP6/2); not calcareous. 4.0

6 Bentonitic mudstone; pale reddish brown (10R5/4) with some olive gray (5Y4/1) calcrete nodules; popcorn weathering; not calcareous. 3.0

5 Bentonitic mudstone; pale red (10R6/2) and pale greenish yellow (10Y8/2); not calcareous. 4.0

4 Sandstone; pale red (10R6/2) and light greenish gray (5GY 8/1); fine-grained, subrounded, moderately well-sorted slightly micaceous dirty sublitharenite; much planar- and trough-crossbedding; not calcareous; forms prominent bench mantled with remnants of unit 5; basal conglomerate is calcrete-nodule rip-up; clasts up to 10 mm; clast-supported; 0.2-0.5 m thick; channels into unit 3 up to 0.3 m; very calcareous. 1.75

3 Bentonitic mudstone; pale red (5R6/2) and pale greenish yellow (10Y8/2); calcareous. 4.25

2 Sandstone and conglomerate; forms a ripple-laminated ledgy break in slope; brownish gray (5YR4/1); sandstone is medium-

grained, subrounded, moderately well-sorted sublitharenite; conglomerate is a calcrete pebble conglomerate with clasts up to 30-40 mm in long axis, most 2-4 mm diameter ;whole is very well-indurated; highly calcareous; locally bone-bearing. 0.2

1 Bentonitic mudstone; pale reddish brown (10R5/4) and darker; produces some unionids; not calcareous. 2.0+

PFNP-10

Section measured in the NE1/4, SW1/4 NE1/4 sec. 34 (unsurveyed), T20N, R24E in the vicinity of locality PFNP-10 (Evanoff, 1994—PFV 10 of Parker, 2002) by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:
Lithodendron Wash Bed:

6 Sandstone; equivalent to unit 8 of Chinde Point II section. not measured

mudstone interval:

5 Bentonitic mudstone; same colors and lithology as unit 3. 2.0

4 Bentonitic mudstone; pale red (10R6/2) to pale reddish brown (10R5/4) with light greenish gray (5GY8/1) spots; not calcareous; very steep slope. 5.75

3 Bentonitic mudstone; predominantly pale red purple (5RP 6/2); silty; not calcareous. 2.5

2 Intraformational conglomerate and conglomeratic sandstone; mottled moderate reddish brown (10R4/6), light gray (N7) and yellowish gray (5Y8/1); sandstone is very poorly sorted, subangular to subrounded muddy sublitharenite; conglomerate clasts are mudstone rip-ups and calcrete pebbles; unit channels up to 1.5 m thick; many unionids; l ensy; calcareous. 0.2-0.3

1 Sandstone and sandy mudstone; yellowish gray (5Y8/1); sandstone is very fine- to fine-grained, subangular to subrounded, moderately well-sorted micaceous sublitharenite; 0.15 m thick or thinner above fossiliferous base that equals Painted Desert Sandstone II; or pale red (10R6/2); similar lithologies but more mudstone and lithics; less micaceous; not calcareous. 8.0+

Black Forest

Section measured in the vicinity of Onyx Bridge (unsurveyed) by A.B. Heckert and C. Davis.

unit lithology thickness (m)

Chinle Group:
Petrified Forest Formation:
Painted Desert Member:

6 Conglomerate; variegated, predominantly pale red (10R6/2) and light greenish gray (5GY8/1) with many very light gray (N8) calcrete pebbles; clasts up to 30-40 mm in diameter common; matrix is very poorly sorted, angular to subangular litharenite; unit may be source of some of bone on slopes of unit 5 but total outcrop is 1.5 m^2 on hilltop; very calcareous. 0.2

5 Silty bentonitic mudstone; slightly darker than moderate pink (5R7/4) with yellowish gray (5Y8/1) and light greenish gray (5GY8/1) reduction spots; some light olive gray (5Y6/1) siderite/calcrete nodules beginning about 4.5 m above base; some remnant crossbeds available in basal portion of unit; not calcareous; forms red slopes above the Black Forest. 14.7

Black Forest Bed:

4 Sandstone interbedded with minor mudstone; sandstones are moderate pink (5R7/4) and yellowish gray (5Y8/1) to light greenish gray (5GY8/1); sandstone is tuffaceous, very poorly sorted angular sublitharenite; many large scale shallow crossbeds with well-indurated ledges up to 1 m thick but often much thinner; steep slopes between ledges; not calcareous; mudstones are same colors and lithologies as unit 5 above. 3.75

3 Heterolithic unit; base is a clayey mudstone that is light greenish gray (5GY8/1) and light brownish gray (5YR6/1); calcareous; above this thin (<1.0 m) base is a very poorly indurated sandstone, the powder of which is very light gray (N8); very muddy, very fine grained sublithic wackestone with mudstone laminations; bulk of unit is intraformational conglomerate and conglomeratic sand-stone; variegated dark greenish gray (5GY4/1) fresh, grading to light greenish gray (5G8/1) weathered clasts are small nodules and rip-ups several mm in diameter; matrix is a medium- to coarse-grained, subangular, poorly sorted litharenite; this unit essentially floors the Black Forest and is highly fossiliferous; contact with overlying unit usually obscured and inferred here; includes petrified logs. 9.0

Thickness of Black Forest Bed: 12.75 m

mudstone interval:

2 Bentonitic mudstone; pale red purple (5RP6/2) with mottles of light greenish gray (5GY8/1); calcareous. 1.5

1 Bentonitic mudstone; pale reddish brown (10R5/4); many calcrete nodules; calcareous; "base" in wash. 5.0+