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LATE TRIASSIC CHARCOAL AND CHARCOAL-LIKE PLANT FOSSILS FROM PETRIFIED FOREST NATIONAL PARK, ARIZONA

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ABSTRACT–Charcoal-like plant fossils, the majority of which appear to be wildfire derived, occur at several different horizons in the lower part of the Chinle Formation of Late Triassic age in Petrified Forest National Park. The most common of these charcoal-like plant fossils are small fragments of black woody material up to1 cm long that are found in situ in the formation. Less commonly, similar small fragments are present on the surface of the formation at two localities where they were left behind as a lag deposit after the enclosing matrix had been removed by erosional processes. Also, charcoal-like material occurs in some of the charred logs and stumps found in the formation. Although there is some small doubt about the taphonomy of some of the material, it is possible that the unusual appearance and low reflectance values of this 'problematic' material, may have resulted from later post-burial mineralization of charcoal. The quantitative reflectance values of most of the in situ and reworked fragments ranges from 2.08-3.12% indicating moderate temperature paleowildfires. In contrast, the reflectance results for a charred stump in the Blue Mesa Stump Field of 2.60-2.80% suggests low-temperature in-situ smoldering. Because the phenomenon of smoldering stumps is commonly seen in modern wildfires this locality may represent the remains of an ancient burnt forest.

Keywords: fossil charcoal, Chinle Formation, Upper Triassic, Petrified Forest National Park, reflected light microscopy, wildfires.

INTRODUCTION

SINCE TOM Harris (1958) wrote a paper entitled 'Forest fire in the Mesozoic', and revitalized a subject, as he put it, "warmly put forward and warmly opposed a century ago", a stream of workers have investigated the occurrence and significance of charcoal-like material in the fossil record. The work produced by these investigators generally supports the hypothesis that most charcoal-like fossils are in fact genuine fossil charcoal, and represented the product of ancient wildfires (Schopf, 1975; Scott, 1989). The process of wildfire charcoalification has been described as 'instant fossilization'; however, several researchers have documented 'problematic' fossil charcoal, often coming from the Permo-Triassic (Jones, 1991). Today, interest mostly lies in the occurrence or relative abundance of charcoal in the fossil record to reconstruct paleoenvironments, understanding the ecological role of ancient fires, interpreting charcoal and vertebrate assemblages, and also possible applications for paleoatmospheric reconstructions.

A technique that has an important role in the study of fossil charcoal is the standard coal petrology method of reflected light microscopy, where the material is embedded in resin and polished. This technique provides limited two-dimensional plant anatomical information, and an assessment of whether previously-stratified cell walls are homogenized, an important characteristic of charcoal (McGinnes et al., 1971). Quantitative reflectance has also found a role, once it was established that there was a correlation between intensity of reflectance and temperature of charcoal formation (Jones et al., 1991), theoretically allowing an estimation of ancient fire temperatures. Researchers could then speculate, for example, whether their fossil material might represent the product of a high-temperature blaze, such as a modern crown fire in a conifer forest, or the low-temperature smoldering of forest litter. However, this speculation is complicated by a number of confounding factors, especially atmospheric oxygen levels, which are liable to influence the nature of the ancient wildfires.

It is well established that there is abundant fossil charcoal in Carboniferous, Jurassic and Cretaceous rocks, and this is reflected in the scientific literature. In contrast, there is a very limited literature on Permo-Triassic fossil charcoal. Some authors have discussed the paucity of charcoal over this period in general terms, for example Scott (2000) notes the 'fewer records' of late Paleozoic and early Mesozoic material. Furthermore, the few papers that do mention Permo-Triassic charcoal tend to concentrate on Permian material. For example, Uhl et al. (2004) record charcoal from a range of depositional settings from the Rotliegend Saar-Nahe Basin in southwest Germany. The Lower Rotliegend (approximately Late Carboniferous) charcoal was found in a range of different sediment types with a wildfire ignition attributed to lightning. In the Upper Rotliegend (approximately Early Permian) charcoal has only been recovered from volcanically-influenced (tuffs or tuffites) deposits. Further, from the size of the material described it may have been entrained in a pyroclastic flow, and thus charred by heat from that flow and not wildfire activity. Uhl et al. (2004) attribute this distribution to an Upper Permian environment with low atmospheric oxygen, sparse vegetation cover, and mechanical breakdown of the macroscopic charcoal fragments under arid conditions. Uhl and Kerp (2003) found charcoal in plant fossil-bearing deposits from the Central European Zechstein (Upper Permian). This material is allochthonous as indicated by the rounded shape of the fragments. Uhl and Kerp (2003) note that "Until now, virtually nothing is known about the fire ecology of the Late Paleozoic, conifer-dominated, upland vegetation".

Fossil charcoal is a common component of coal; usually described as the macerals fusinite and semifusinite, within the inertinite group. This occurrence is unsurprising given the regular wildfires that burn in a variety of coal-forming environments (Ahlgren, 1974; Cohen, 1974; Moore, 1978; Racine et al., 1985; Sanford et al., 1985). A major fire event in a late Permian coal has been identified by Glasspool (2000). Petrographic and mesofossil analyses of a layer dominated by semifusinite in the Lower Whybrow coal in New South Wales, showed that the fire effected both the vegetation and the mineral content of the coal following the fire. Semifusinite is characterized by generally lower reflectance of polished surfaces when compared with fusinite, thus suggesting low fire formation temperatures (Jones et al., 1991). A reconstruction of the Permian fire event suggests a smoldering low-temperature burn, and Glasspool (2000) speculates that fires could have been an integral part of many Gondwana coal-forming ecosystems. It is useful to observe that in circumstances favorable to the preservation of fossil plant material, such as coal, fossil charcoal is often an important component.

Two Permo-Triassic localities with vertebrate and charcoal assemblages have been intensely researched. The Lower Permian Geraldine Bonebed of Archer County Texas, USA, consists of an assemblage of articulated tetrapod skeletons, remains of other vertebrate taxa, plant compression fossils and fossil charcoal (Sander, 1987). This assemblage has been interpreted as a single mass death event that resulted from a forest fire that drove the animals into a pond where they perished. It is assumed that the vegetation must have been of sufficient density and the fire of sufficient intensity to have forced the animals into taking such a course. The Upper Triassic Snyder quarry is located in north-central New Mexico, and has an assemblage of vertebrate fossils with "substantial" amounts of fossil charcoal (Zeigler, 2003). Evidence suggests minimal transport and rapid burial of the bonebed. Quantitative reflectance of the charcoal fragments, 1.2% - 2.1% suggests a moderate wildfire temperature in the range 300-450°C. The scenarios for both localities appear similar, with natural wildfires leading to animals seeking refuge in water, drowning, and their remains being preserved due to rapid burial with the fossil charcoal from the fire.

The occurrence and paleobotany of Late Triassic charcoal in Petrified Forest National Park, Arizona has been reported by Jones et al., 2002. This work builds on that paper, in particular looking at the reflected light microscopy of that material, and the paleoecological and taphonomic implications from those results. Schuneman and Uhle (2003) have also examined material from the Petrified Forest, undertaking an organic geochemical analysis to identify pyrogenic Polycyclic Aromatics Hydrocarbons (PAHs). Their research is based on the PAH database published by Yunker et al., (2002), and in particular concentrates on the ratios of 6 PAHs found in modern wood charcoal and bituminous coal. The work of Schuneman and Uhle (2003) concludes that the relative abundances of the pyrogenic PAHs in modern, Carboniferous and Triassic charcoal could reflect differences in atmospheric oxygen levels. However they do concede that their conclusions are founded on a small PAH database (Yunker et al., 2002) and uncertainties exist about the formation origins and later taphonomic history of the Petrified Forest Triassic 'charcoal'.

Paleoatmospheric reconstructions of the Permo-Triassic indicate low atmospheric oxygen and high carbon dioxide (Beerling et al., 2002). Although different reconstruction methods have produced different absolute values, the overall atmospheric composition is not seriously disputed. For example, Berner and Canfield (1989) suggest that from a high of ~35% oxygen during the Carboniferous, levels could have fallen to ~15% oxygen in the Triassic. Milo (2004) suggests the lower level of 12% oxygen for the Permo-Triassic boundary. Carbon dioxide, on the other hand, is believed to have increased, possibly as much as 9-fold from the early Permian to middle/late Triassic (Montanez et al., 2000a, 2000b), with an Early Permian peak of 2,000-2,500 ppmV. Milo (2004) suggests a CO_2 level of 2,000 ppmV at the Permo-Triassic boundary. Reconstructed variations in the atmospheric O_2/CO_2 (%) mixing ratio (Beerling et al., 2002, their figure 6) suggest values for the Carboniferous-Permian boundary of ~500 (lowest estimate) to ~1,500 (highest estimate), Permian-Triassic ~50 (lowest estimate) to ~500 (highest estimate), Triassic-Jurassic ~50 (lowest estimate) to ~300 (highest estimate). It is noted that the error margins in the Beering et al. model indicate that theoretically the Paleozoic oxygen maximum could occur at any point from the Tournaisian to the Guadalupian, while the oxygen minimum could occur from the mid-Triassic to mid-Jurassic. However, given the paucity of charcoal in the Permo-Triassic, it is reasonable to take the mid-range modeled values when considering possible relationships between charcoal production and paleoatmospheric oxygen levels.

The locality numbers used in this article are the numbers now assigned to the charcoal localities in the records of the Petrified Forest National Park. Where appropriate they are cross referenced with locality numbers used in previous publications. Qualified investigators may obtain their exact locations from the Chief of Resource Management, Petrified Forest National Park.

MATERIALS AND METHODS

The charcoal fragments were found in two main forms, *in-situ* and lying loose on the surface, depending upon the locality. Locality PFP 098 (= locality 1 of Jones et al., 2002) , an arroyo called Dry Wash cutting through what is

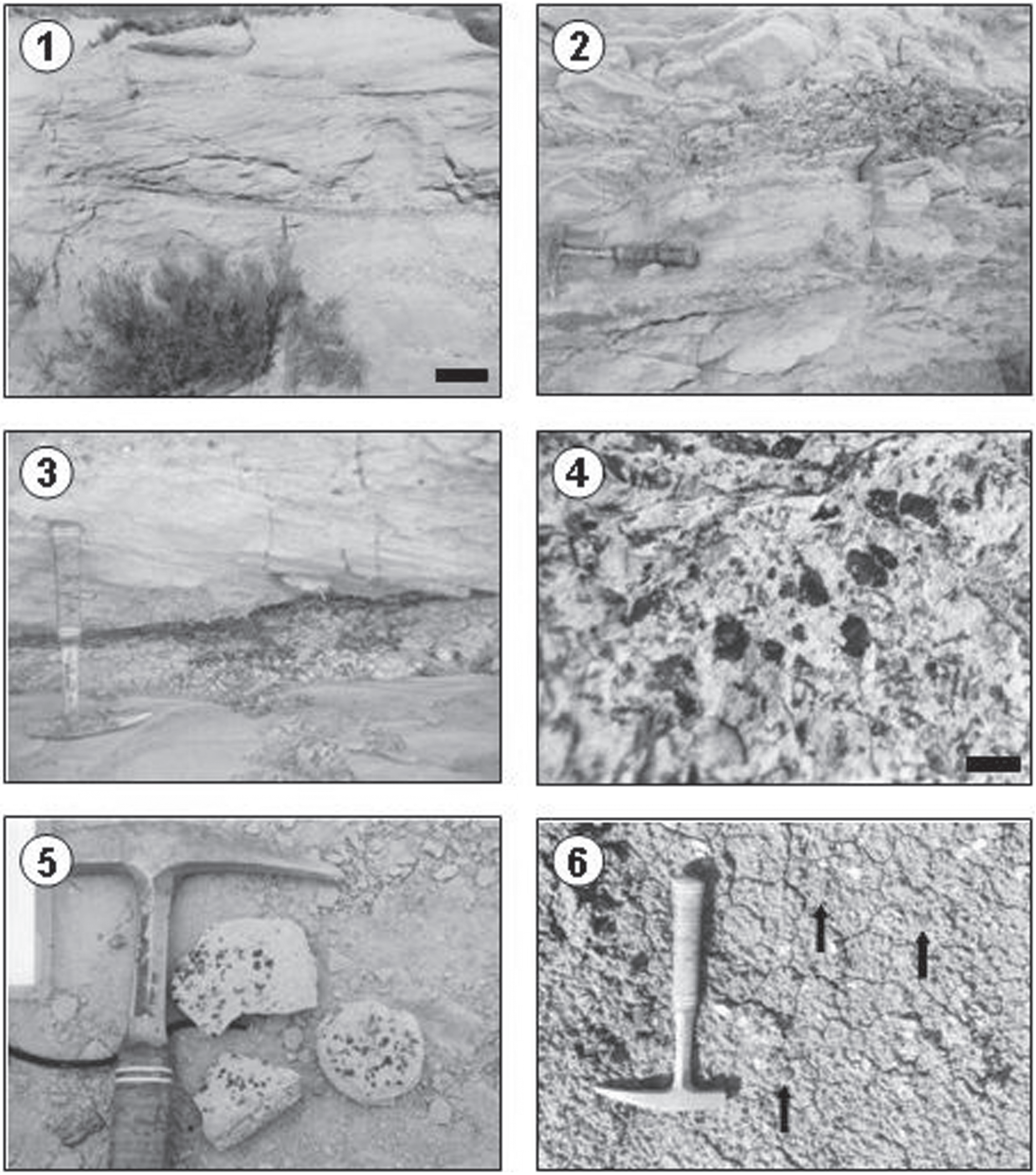

Figure *1*. *1*. Bedforms in Jim Camp Wash beds at locality PFP 098 with abundant charcoal concentrated at the base. Charcoal plant fossils were found in a number of these bedforms along Dry Wash. Scale bar = 50 cm; *2*. Detail of the concentrations of charcoal fragments towards the base of the large bedforms in the Jim Camp Wash beds in Dry Wash near locality PFP 098; *3*. Approximately 1 meter long plant compression fossil, believed to represent a single log exposed in the wall of Dry Wash. The plant material is preserved as vitrinite; however it was too degraded to obtain reliable reflectance data from embedded and polished surfaces; *4*. Detail of the black fragments of charcoal in the pale beige clastic matrix of the Jim Camp Wash beds at locality PFP 098 in Dry Wash. Scale bar = 1 cm; *5*. Samples of charcoal collected in the field from locality PFP 098. These fragments were manually extracted from the matrix, embedded, polished, and examined under reflected light microscopy; *6*. Surface exposure at locality PFP 025 near the Tepees. The dark grey 'charcoal' is poorly seen (arrows) against the background of the grey mudstone. The small white crystals are gypsum, which was a common association with the exposed 'charcoal-like' fossils.

Figure *2*. The stump in the Blue Mesa Stump Field (locality PFP 066) that was the source of some of the charcoal discussed here. Blue Mesa is just below the horizon and a second stump is indicated by the arrow.

now considered to be a local sandstone bed in the Jim Camp Wash beds of the Sonsela Member (Parker, this volume), has an abundance of *in situ* charcoal fragments concentrated in the bases of large bedforms (Fig. 1-1 and 1-2). Proximal to the charcoal, large compression fossils of isolated logs were found preserved as vitrinite (Fig. 1-3). The charcoal fragments recovered from this locality were still in the clastic matrix (Fig. 1-4 and 1-5). This sandstone is poorly cemented, and it was easy to manually extract the fossil plant fragments with a sharp scalpel. The fossil material is also highly friable, and shows signs of white oxidation on a number of the specimens.

The fragments recovered from locality PFP 025 (= locality 2 of Jones et al., 2002) were lying loose on the surface of a dark green mudstone (Fig. 1-6) in the Newspaper Rock bed in the Tepees area, and are much more robust than the locality PFP 098 material. That this material was derived from the green mudstone is indicated by the fact that it was only found on the surface of this lithology, and had not undergone any modern transport or rounding. As described by Jones et al. (2002), the robustness of the locality PFP 025 material is due to mineral material infilling the open cellular structure of the charcoal (Jones et al., 2002, Plate IIId). The paleobotany of the fragments reveals that they are all composed of wood derived from pycnoxylic wood previously identified from the Upper Triassic of Arizona.

Locality PFP 066 is east of the Tepees in the Blue Mesa Stump Field and contains *in situ* fossil tree stumps (Fig. 2). Anatomically, the material consisted of pycnoxylic wood generally comparable to that of the *Araucarioxylon arizonicum* tree. The stump field lithology is very similar to that at locality PFP 025 in the Tepees area; however, the stump field is slightly higher in the stratigraphic column in the upper part of the Blue Mesa Member of the Chinle Formation (Parker, this volume). Some of the fossilized stumps at locality PFP 066 have been mapped and the results reported and discussed by Ash and Creber (1992). A detailed account of the stratigraphy and geological history of localities PFP 098 and PFP 025 is given in Jones et al. (2002) and that of locality PFP 066 is given in Ash and Creber (1992).

The embedding of the charcoal fragments in epoxy resin for polishing and reflected light microscopy proved to be highly problematic and time-consuming. This was not unexpected as difficulties have been encountered with previous Permo-Triassic material from other localities (Jones, 1991). The embedding of fossil and modern charcoal is somewhat difficult (Jones and Rowe, 1991 and chapters therein), with problems such as difficulty impregnating resin into the body of the charcoal fragments, the trapping of air pockets, fragments floating on the resin surface, charcoal 'plucking' from the resin during polishing, and mineral scratches on the polished face. Jones and Rowe (1999) suggest a number of potential solutions, including; vacuum-impregnation of the resin, low viscosity resins, painting the fragments with superglue prior to resin embedding, and 'painting' the polishing face with resin at regular intervals during the polishing to minimize 'plucking'. The Petrified Forest material described in this paper needed several

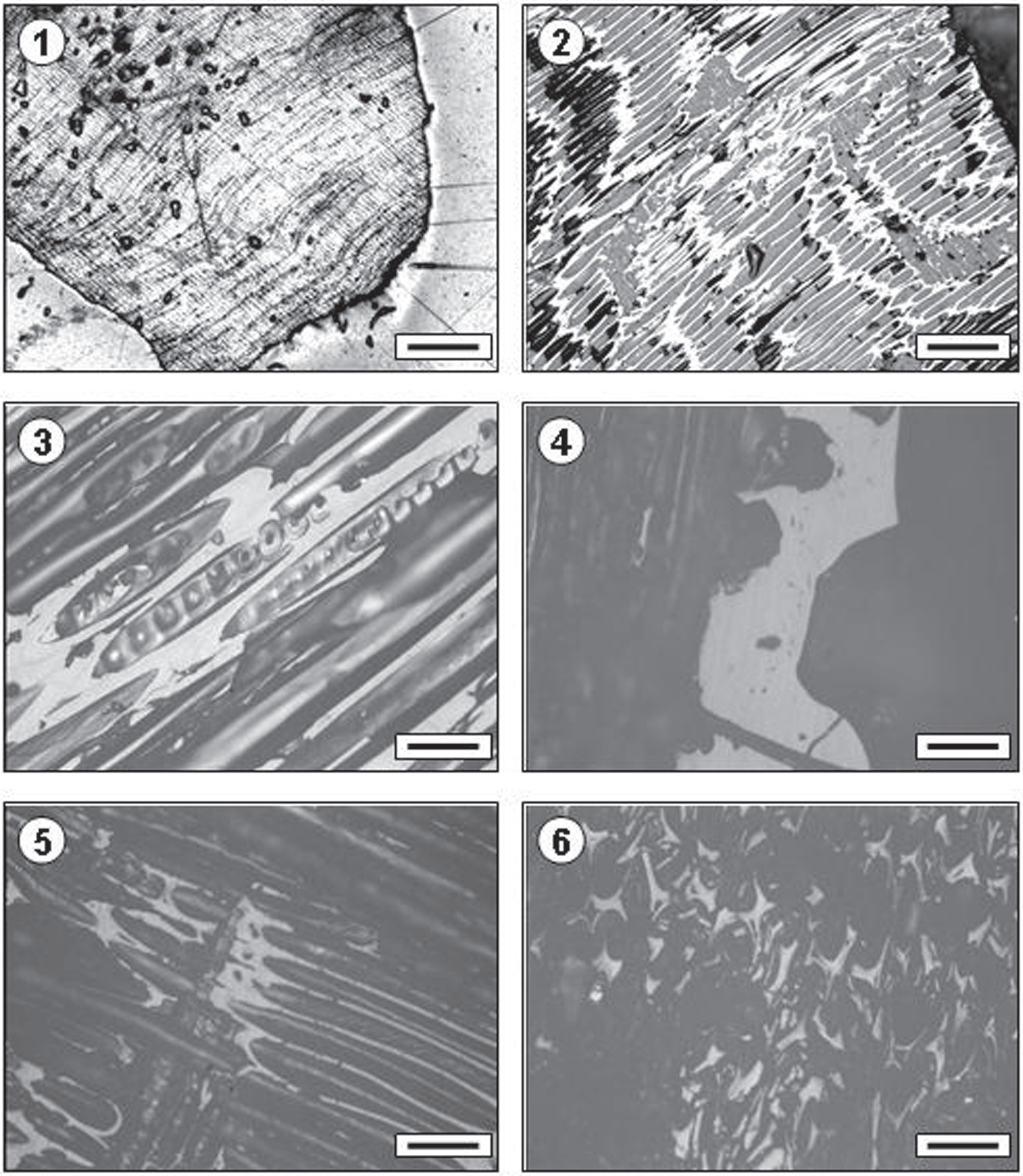

Figure *3*. Photomicrographs of charcoal from Petrified Forest National Park, Arizona. *1*. Embedded and polished 'charcoal' fragment. Locality PFP 025. Scale bar = 350 mm; *2*. Embedded and polished charcoal fragment in which there is high contrast between the high reflectance charcoal and the embedding resin seen in the top right corner. Locality PFP 098. Scale bar = 100 mm; *3*. Poorly visible uniseriate pitting. The embedded and polished material has limited palaeobotany applications. Locality PFP 098. Scale bar = 50 mm; *4*. Low reflecting cell wall. The polished face cuts obliquely through the plant's cell wall with the result that a good area is available for taking quantitative reflectance values. The cell wall is also homogenized, a critical parameter used to recognize charcoal. Locality PFP 098. Scale bar = 30 mm; *5*. Extremely thin cell walls, highly problematic for obtaining quantitative reflected light readings. Poorly visible cross-field anatomy. Locality PFP 098. Scale bar = 30 mm; *6*. "Bogenstruktur", a mass of tiny fragmented pieces of charcoal. A commonly observed feature of fossil charcoal it is believed to represent fragile and brittle fossil material that has been mechanically crushed during burial. Locality PFP 098. Scale bar = 33 mm.

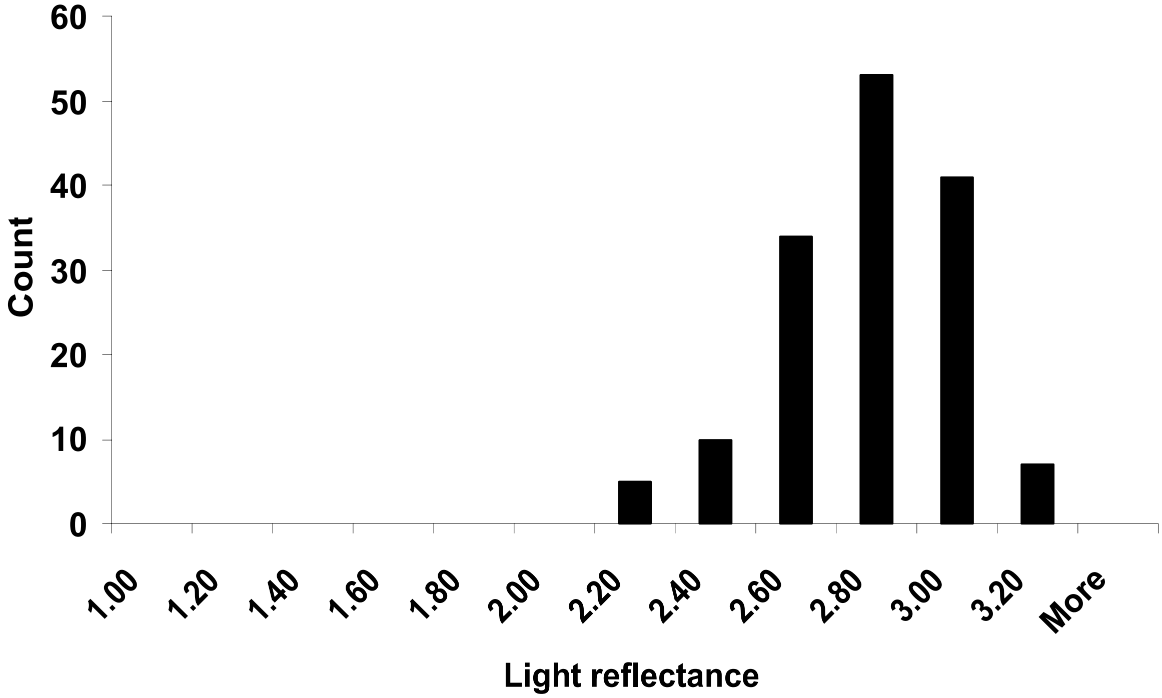

Figure *4*. Charcoal from locality PFP 098 in the Jim Camp Wash beds in Dry Wash. Histogram of 150 reading of reflectance under oil of a polished surface. Minimum = 2.08%, maximum = 3.12%, mean 2.68%, std. error = 0.019, std. dev. = 0.229.

coats of 'painted' Epotek 301 resin during polishing to prevent 'plucking'. Despite efforts, a proportion of the material selected from localities PFP 025 and PFP 098 could not be satisfactorily embedded and polished, and attempts to do so were eventually abandoned. Some vitrinite from the compressed logs at locality PFP 098 was also embedded and polished, with the intention of obtaining comparable vitrinite reflectance values; unfortunately it was concluded that the material was too degraded to give reliable results.

The polished block surfaces were examined using a LEICA DMR reflected light microscope. The observations and measurements were made under oil (SG 1.5) using x100 (observation only), x40 and x20 lenses. Percentage reflectance was measured using LEICA QWIN image analysis software, a light source filtered to 546 nm, and the system was calibrated with McCrone specular reflectance standards; GGG (R_{oil} 1.726), YAG (R_{oil} 0.917), and silica glass (R_{oil} 0.038). The number of measurements was governed by the amount of material exposed on the polished face, and the quality and dimensions of the exposed material.

REFLECTED LIGHT MICROSCOPY RESULTS

A low resolution reflected light image of a fragment of 'charcoal' from locality PFP 025, embedded in resin and polished, is shown in Fig. 3-1. The macroscopic rounded shape is apparent, as is the preservation of wood anatomy. A number of large scratches can been be seen as black lines across the image, these scratches were avoided when selecting points for reflectance measurement. Despite these scratches, overall, the quality of the polished surface was good. It is impossible to accurately gauge the quantitative reflectance of the fossil material from the images, due to light level compensations made by the camera to obtain good pictures. However, an indication is given by comparing the grey tones of the exposed fossil with the embedding resin; the fossil material is only just brighter (higher reflecting) than the surrounding resin. Fig. 3-2 shows a low-resolution image of an embedded and polished charcoal fragment from locality PFP 098. Again there is good preservation of wood anatomy, however in this example, there is a strong contrast between the high-reflectance (white) plant cell walls and the dark grey (almost black) embedding resin exposed in the top right-hand corner of the image. This indicates the much higher reflectance of the material from locality PFP 098, when compared with the locality PFP 025 material.

The amount of anatomical information that can be obtained from the embedded and polished material is limited. Fig. 3-3 shows uniseriate bordered pits. Fig. 3-4 shows homogenized cell walls, an important characteristic of fossil charcoal. Fig. 3-5 shows three-dimensional preservation of very thin cell walls, with 'checking ' and crossfield pitting. Under scanning electron microscopy, the surface of the 'charcoal' fragments covered in fine fragments, or 'bogenstruktur', was described by Jones et al. (2002) for the locality PFP 025 mate-

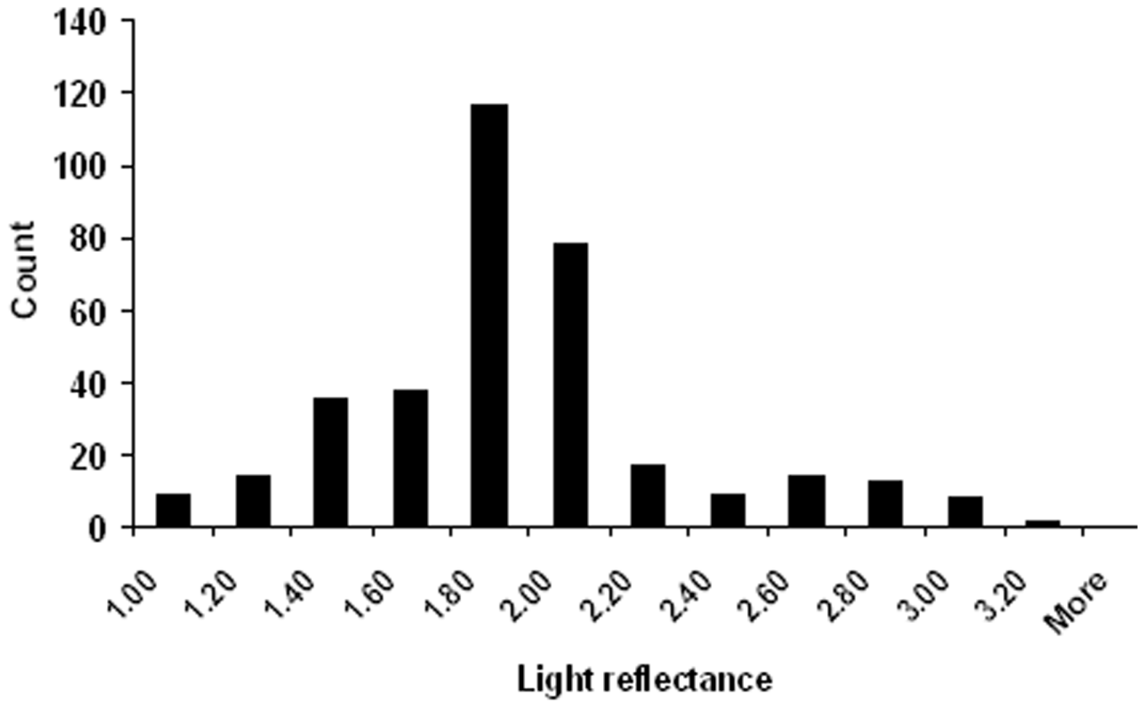

Figure 5. Charcoal (?) from the Newspaper Rock bed at locality PFP 025 in the Tepees area. Histogram of 350 reading of reflectance under oil of a polished surface. Minimum = 0.78%, maximum = 3.12%, mean 1.78%, std. error = 0.029, std. dev. = 0.409.

rial. This can be seen in Fig. 3-6, where a collection of tiny isolated cell wall fragments can be seen against the grey background of the embedding resin. It is problematic to obtain reliable quantitative reflectance values for such small cell wall fragments; however, results were obtained that indicated relatively low reflectance values. A simple, qualitative method to validate those results is to compare the RL percentages obtained with those obtained from larger fragments where the grey-level contrast between the fossil material and embedding resin is comparable; for example with Fig. 3-4.

The histograms for percentage reflectance under oil (R_{oil}) are shown for the three suites of material in Figs 4, 5 and 6.

DISCUSSION

The obvious question, which is still to be definitively answered, is whether or not all the fossil material collected in the Petrified Forest Park is true charcoal, the end product of ancient fires. The material from locality PFP 098, in the Jim Camp Wash beds in Dry Wash, is almost certainly genuine wildfire charcoal, as it possessed all the macroscopic and microscopic characteristics defined by previous researchers to recognize fossil charcoal (Scott, 1989). The material from locality PFP 025, in the Newspaper Rock bed near the Tepees, possesses many of the required characteristics, but not all of them. Macroscopically, the material is highly robust, most fossil charcoal can be crushed by finger pressure, and this material cannot be crushed. The highly robust nature of the material was probably critical to it remaining intact on the exposed surface, as more delicate material would be rapidly destroyed. Instead of the usual black luster seen in fossil charcoal, the Tepees material has a dark grey sheen. The robust nature and grey sheen are almost certainly due to the 'mineralized' nature of the fossils, as recognized by the in-filled cells when viewed under SEM (Jones et al., 2002).

In addition to their appearance, there is a clear difference in the qualitative reflectance of these two fossil suites (Fig. 4, 5). The reflectance data (Fig. 4) supports the view that the material from the Jim Camp Wash beds is charcoal. The values falling in the range 2.08-3.12% would suggest fire formation temperatures around 400-500°C, based on the experimental work of Jones et al. (1991). This fire temperature range is slightly higher than the 300-450°C proposed by Zeigler (2003), but the difference is probably not that significant. The loose Newspaper Rock bed material has a much broader range of reflectances (Fig. 5), from 0.78 – 3.12%. The lower reflectance values would correspond to a fire temperature just above 200°C, so theoretically the material could still be charcoal. If the material is charcoal, we speculate that the lower reflectance values might be related to the mineralization that the fossils have undergone; however this does not; as yet, offer a mechanism of how the reflectance might be lowered. The taphonomy would require that the mineral matter not only infilled open cellular spaces, but also impregnated the cell wall material itself.

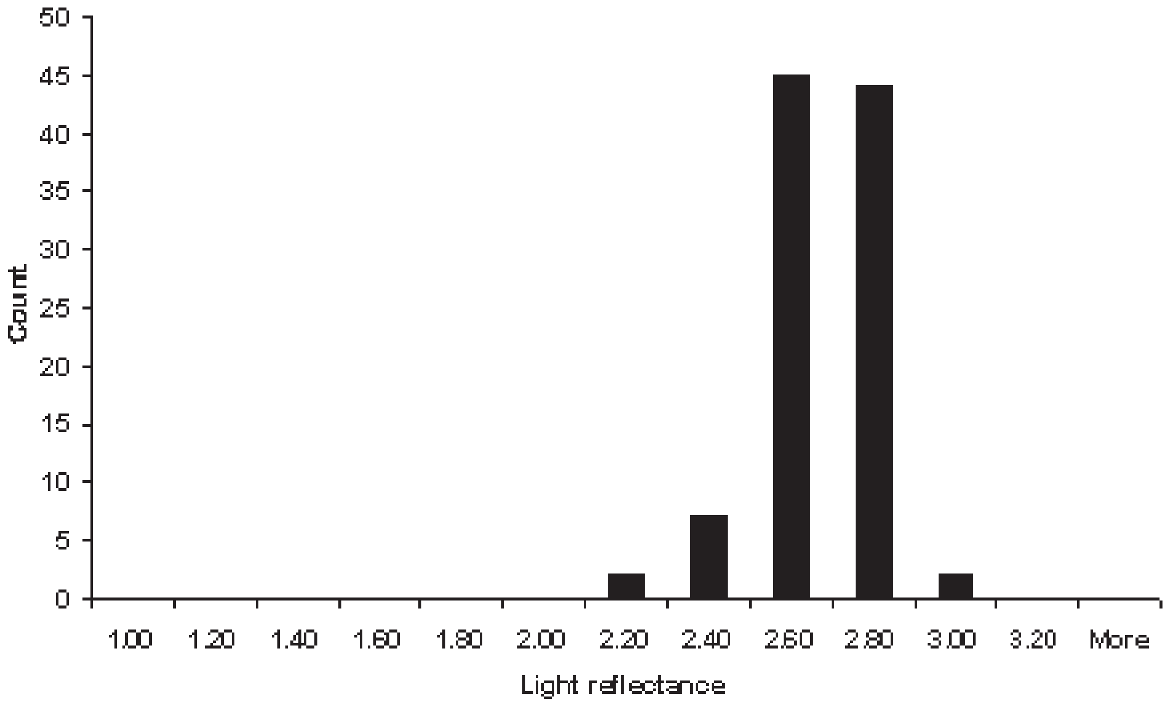

Figure *6*. Charcoal from a stump at locality PFP 066 in the Blue Mesa Stump Field; coalified (charcoalified) stump. Histogram of 100 reading of reflectance under oil of a polished surface. Minimum = 2.17%, maximum = 2.94%, mean 2.57%, std. error = 0.014, std. dev. = 0.142.

The reflectance values of the material collected from the 'charred stump' at locality PFP 066 in the Blue Mesa Stump Field (Fig. 6) appear at face value to be less problematic. The stump mean reflectance value at 2.57% is fractionally below that of the Jim Camp Wash beds charcoal at 2.68%; however, importantly the bulk of the material falls in the range 2.60-2.80%, with little higher reflecting material. This agrees with the scenario of a Triassic *in-situ* stump smoldering at low to moderate temperatures; a well-established phenomenon in modern forest fires. What is not explained is how the charred stump charcoal appears to have avoided the mineralization that affected the other loose Tepee material at locality PFP 025. Further work is required, in particular sampling many more stumps, to determine if the fossil forest reported by Ash and Creber (1992) is in fact a burnt fossil forest.

For reconstructions of fire history in ancient ecosystems, one of the crucial parameters is the paleoatmospheric oxygen levels. It is well established by simple experiments and anecdotal evidence about accidents in medical oxygen tents, that fires are more likely to ignite, and burn fiercer and hotter in elevated atmospheric oxygen conditions. At first consideration, it is reasonable to assume that given adequate fuel supplies a Carboniferous fire with 35% atmospheric oxygen would be more likely to ignite, and burn fiercer and hotter than a Triassic fire with 15% atmospheric oxygen: thus there is an abundance of Carboniferous charcoal and paucity of Triassic charcoal in the fossil record. But it is not that simple, because charcoal is produced under conditions where oxygen is limited (Rabash and Langford, 1968); thus it might be that a moderate Triassic fire could produce more charcoal than a fierce Carboniferous blaze that completely combusted the majority of the available fuel.

Could it therefore be that the more important question was not the relative amounts of charcoal produced, for example, during the Triassic or Carboniferous, but instead how much of that charcoal was deposited in a setting where it was preserved in the fossil record? Certainly the Permo-Triassic fossil assemblages of vertebrate fossil and charcoal (Sander, 1987; Zeigler, 2003) support the notion that if the charcoal is very rapidly buried in appropriate sediment types, then it will be preserved. The taphonomy of charcoal thus becomes of crucial importance, and notions on the 'inertness' of charcoal once buried need to be reconsidered. It is well-known that charcoal will withstand weeks in powerful oxidizing agents such as concentrated nitric acid, a chemical environment that will rapidly breakdown non-charcoalified plant fossils; however, this probably does not supply a comparable metric for longer-term burial conditions. Carboniferous charcoal samples collected by the senior author 20 years ago, survived in good condition for hundreds of millions of years when encased in rock, but 20 years in a storage cupboard and atmospheric exposure has resulted in clear degradation on the charcoal surfaces; taking the form of a white powdery surface and powdery texture. It is also self-evident that coal, and charcoal in coal, is preserved because the burial conditions are satisfactory for fossil plant preservation. Because we know that fires occurred in the Permo-Triassic, it would be more surprising if these coals did not contain a significant proportion of charcoal. It is also possible that the severity of the fires themselves also contributed towards the preservation of the charcoal. Fires can devastate vegetation cover on soil, and this can result in greatly enhanced rates of erosion; values of 30 times that of normal have been recorded following fires (Swanson, 1981); the fires thus helping to generate their own sediment cover.

CONCLUSIONS

We conclude that the majority of charcoal-like plant fossils collected from the Petrified Forest do represent fossil charcoal, the final product of ancient wildfires. There is little doubt about this assessment for localities PFP 098 (Dry Wash) and PFP 066 (Tepees area); however there is still some small doubt about the genesis of the locality PFP 025 (Blue Mesa Stump Field) material. Having said that, a plausible alternative preservation mechanism that could have produced the locality PFP 025 material has yet to be suggested. We speculate therefore that the slightly unusual macroscopic appearance and low reflectance values, could result from later mineralization of genuine charcoal.

The quantitative reflectance values obtained are not too dissimilar to previous published results, and from comparisons with modern experimental work, indicate moderate temperature wildfires. A slight refinement to this story is seen in the reflectance results for the charred stump, which are slightly lower than the locality PFP 098 results, and have been interpreted as a low-temperature smoldering in-situ stump. This phenomenon of smoldering stumps, often smoldering for considerable periods, is commonly seen in modern wildfires. An implication of this finding is that the stump field that was previously considered (Ash and Creber, 1992) to be the remnants of an ancient forest might now be considered to represent the remains of a burnt ancient forest, a much more unusual occurrence.

It is questionable how much significance can be placed on the apparent lack of fossil charcoal in late Paleozoic and early Mesozoic rocks, in terms of paleoatmospheric oxygen levels. The relationship between charcoal production and atmospheric oxygen would appear to be the subject of contradicting positive- and negative-feedback cycles. For example, it cannot be assumed that the high oxygen Carboniferous should have been a time of regular, fiercely burning wildfires, because the very abundance of oxygen would mean that the fires would be unlikely to leave much charcoal as limited oxygen is a requirement for charcoal formation. On the other hand, the low atmospheric oxygen levels of the Triassic should have experienced fewer and less severe wildfires, but the lower oxygen levels should have resulted in enhanced charcoal production. Thinking in broad generalizations, the putatively more severe fires of high oxygen times, such as the Carboniferous, are likely to have had more severe impacts on the paleoecosystems, when compared with the possibly more moderate fires of low oxygen times such as the Triassic. These impacts could have included fires denuding vegetation cover, resulting in enhanced erosion and sediment production; thus resulting in more favorable conditions for the rapid burial and therefore preservation of charcoal in the fossil record.

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