geosciences

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Mineralogy of Eocene Fossil Wood from the "Blue Forest" Locality, Southwestern Wyoming, United States

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Received: 7 December 2018; Accepted: 7 January 2019; Published: 10 January 2019

Abstract: Central Wyoming, USA, was the site of ancient Lake Gosiute during the Early Eocene. Lake Gosiute was a large body of water surrounded by subtropical forest, the lake being part of a lacustrine complex that occupied the Green River Basin. Lake level rises episodically drowned the adjacent forests, causing standing trees and fallen branches to become growth sites for algae and cyanobacteria, which encased submerged wood with thick calcareous stromatolitic coatings. The subsequent regression resulted in a desiccation of the wood, causing volume reduction, radial fractures, and localized decay. The subsequent burial of the wood in silty sediment led to a silicification of the cellular tissue. Later, chalcedony was deposited in larger spaces, as well as in the interstitial areas of the calcareous coatings. The final stage of mineralization was the precipitation of crystalline calcite in spaces that had previously remained unmineralized. The result of this multi-stage mineralization is fossil wood with striking beauty and a complex geologic origin.

Keywords: Fossil wood; Blue Forest; Eden Valley; Lake Gosiute; chalcedony; quartz; calcite; stromatolite; Green River Basin; Wyoming

1. Introduction

This report describes the fossil wood preserved in Eocene lakebed sediments in southwestern Wyoming, USA. The purpose of our research is to investigate the fossilization processes that produced the complex mineralogy of Blue Forest wood. Taxonomic and paleoecology studies of stratigraphically similar sites within the Green River Formation provide insights into the paleogeography and paleoclimate associated with the Blue Forest. Fossil wood from the region is sometimes referred to as coming from Eden Valley, a broad basin that does not have well-defined boundaries. In this report, we use the locality name "Blue Forest" to describe an area that has long been known to petrified wood aficionados as the Blue Forest. The name comes from the bluish-gray color of the chalcedony that fills the open spaces in many specimens. The fossil wood has a complex mineralogy, resulting from environmental changes in the ancient lake basin, and the subsequent diagenetic processes.

2. Geologic Setting

The beginning of the Green River basin can be traced to the Laramide Orogeny, a tectonic episode that began in the Late Cretaceous and ended in the late Eocene. From the late Paleocene to the middle Eocene (55–38 MA), the Green River Lake System covered large areas of western USA, having one of the longest durations of any known lake system [1]. During the middle early Eocene, three separate lakes coexisted—Fossil Lake, Lake Uinta, and Lake Gosiute—each lake occupying a down-warped basin that accumulated sediment from the adjacent highlands (Figure 1). Lacustrine deposition was mostly a continuous process, occurring on broad flood plains and complicated by the transgressions and regressions caused by tectonic subsidence, climate change, and episodic volcanic activity [2]. By the late middle Eocene, only Uinta Lake remained, much reduced in size.

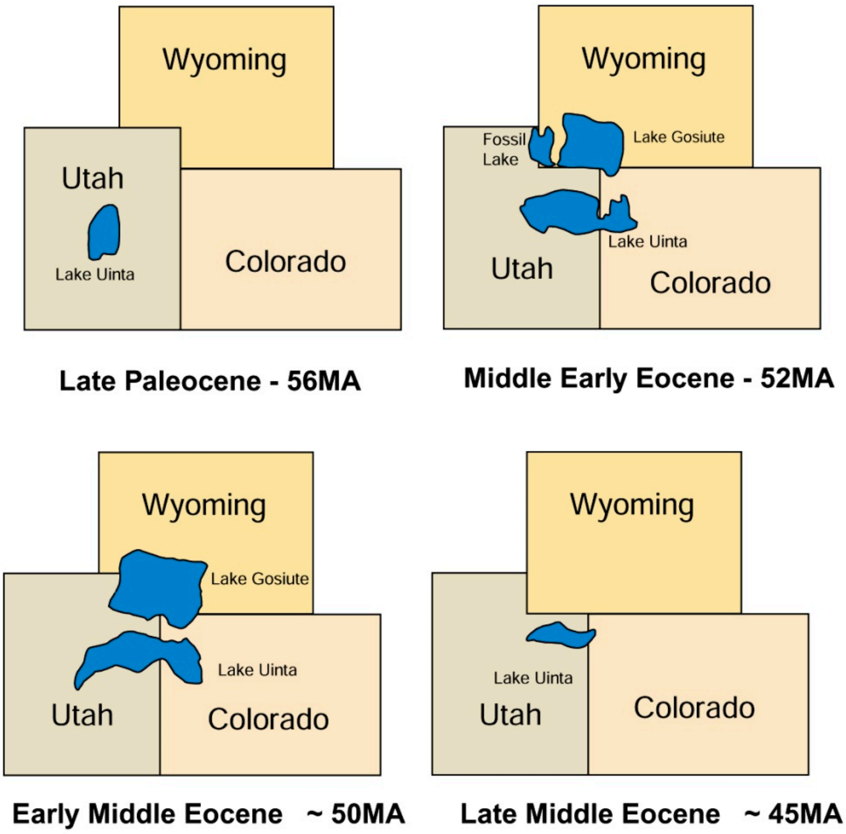

Figure 1. Green River Lake basin map modified from [1].

The fossil wood described in this report is associated with ancient Lake Gosiute. This lake persisted for at least five million years, from approximately 53 to 49 MA. This history is recorded by approximately 838 m of lacustrine deposits, predominately composed of limestone, sandstone, and shale [3]. Clastic sediments are rich in volcanic material transported by streams from the Absoroka Volcanic Field in northwest Wyoming, USA. The basic structure of the region remained unchanged during the life of Lake Gosiute, but the sediments record episodes of transgression, regression, and climate change. During times of regression, the lake water commonly became saline, as evidenced by the abundant evaporite minerals found in some of the stratigraphic members. From a regional geologic perspective, the original Lake Gosiute lake basin was subsequently divided into two structural basins that are now separated by the Continental Divide. Fossil wood is preserved in both the Green River Basin and the Great Divide Basin. Five popular collecting localities (Figure 2) are located in the Lake Gosiute lacustrine strata within the upper Green River Formation and the overlying Bridger Formation (Figure 3). The detailed geology of this region can be found in a recent map [4].

The upper members of the Green River Formation are overlain by and interfinger with mostly the fluvial sediments of the Bridger Formation. The younger Bridger Formation beds are dominated by limestone, but the oldest beds are rich in volcaniclastic sediment transported from the Absoroka Volcanic Field, and resemble the composition of the youngest Lake Gosiute sediments. For this reason, contacts between the Green River and Bridger Formations may not be readily distinguishable [5,6].

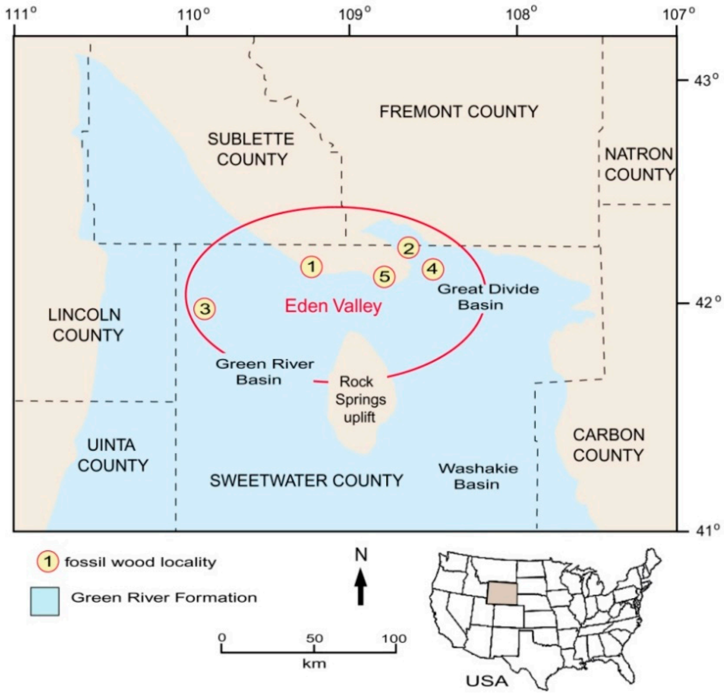

Figure 2. Fossil wood localities: (1) Big Sandy Reservoir; (2) Oregon Buttes; (3) Blue Forest; (4) Parnell Draw; (5) Hay's Ranch.

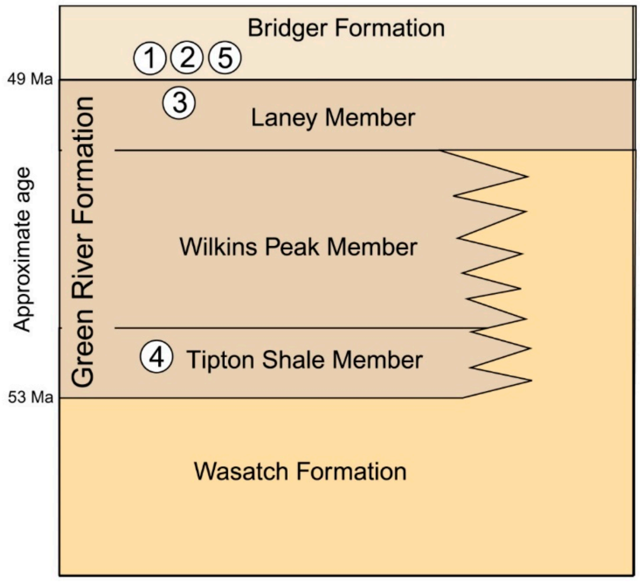

Figure 3. Generalized stratigraphy of the Eocene sediments in the Green River basin, showing the relative position of the fossil wood localities. (1) Big Sandy Reservoir; (2) Oregon Buttes; (3) Blue Forest; (4) Parnell Draw; (5) Hay's Ranch. This diagram is a simplification; stratigraphic members typically have interfingering contacts.

3. Paleontology

Taken together, these three lake basins represent an important Fossil Lagerstätten that provides a window into early Paleogene freshwater ecosystems (Figure 4). The paleontology of the Green River Formation has been reviewed by Grande [1,7], who emphasized the Fossil Lake deposits. The three Green River Lakes have distinctive fossil assemblages. Fossil fish were reported as early as 1856, and by the 1870s, commercial quarrying had begun at several Fossil Lake localities, an activity that continues today. Fossil Lake was originally described as "unnamed Green River Lake west of Gosiute

Lake" [8]. Despite its small size and brief duration, Fossil Lake is a prolific source of vertebrate fossils. In 1972, Fossil Butte National Monument was established to protect a small part of the fossil beds. Fossil fish are the best-known Green River Formation fossils, but other vertebrate remains include birds, reptiles, and mammals. The Lake Uinta sediments include extensive shale deposits that locally preserve abundant leaf fossils and pollen, as well as fossil insects and shorebird tracks [9–18].

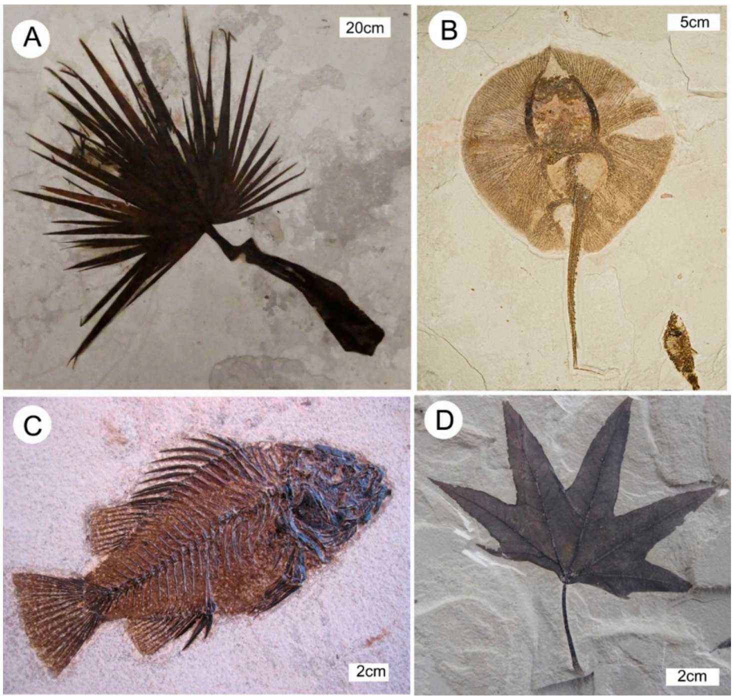

Figure 4. Green River Formation fossils. (**A**) Palm frond, *Sabalites powelli*. Photo courtesy of Richard Dillhoff. (**B**) Stingray, *Heliobatis radians*. (**C**) Fish, *Priscacara serratus*. (**D**) Sycamore leaf, *Macginitea wyomingensis*.

The sediments from Lake Gosiute preserve leaf impressions and vertebrate remains, but the most abundant fossils are silicified logs and limbs—the subject of this report. Lake Gosiute has been described as a playa lake complex [19,20]. The sediments record large fluctuations in the position of the shoreline. At times the broad, shallow lake became quite saline. Eutrophic conditions limited fish habitats, favoring suckers and catfish [7], in marked contrast to the diverse fish populations that flourished in the waters of Fossil Lake. Thick algal mats covered much of the lake bottom several times during the lake's history [20]. As described later, the proliferation of algae and cyanophytes was a factor in the fossilization process that preserved ancient wood.

Lake Gosiute was at its greatest areal extent during the time of the deposition of the Laney Shale Member [21]. The subsequent reductions in the size of Lake Gosiute may have been caused by an influx of alluvial sediment and/or a reduction in precipitation. The final limnological evolution of the lake has been interpreted as a transition from a saline, alkaline lake to a freshwater lake, representing a change from a closed basin to an open basin [22]. This change to a more fluvial environment is evidenced by the lacustrine deposits of the Bridger Formation. The lake became smaller and shallower, episodically filled by volcaniclastic deposition, then reappearing when the basin subsidence exceeded sedimentation [5,23]. Tectonic activity may have also played a role in the sedimentary processes [24].

The final demise of Lake Gosiute occurred in the middle Eocene at ca. 44 Mya [1,7]. This phenomenon was partly related to the delivery large volumes of volcaniclastic sediment caused by eruptions in the Absoroka volcanic field, in what is now southwestern Montana and northwest Wyoming, USA [25]. In the source area, volcaniclastic mudflows preserved the extensive fossil forests at Yellowstone National Park [26]; the mineralogy of these fossil woods is relatively simple, where silicified trunks are preserved in an upright position. In contrast, the approximately contemporaneous fossil forest of southwestern Wyoming shows multistage mineralization caused by the rapid environmental changes that occurred along the shoreline of a shallow lake. Ultimately, the demise of the Green River basin lakes was related to a drying trend. The early middle Eocene Lake Gosiute fossil woods have subtropical affinities, but Late Eocene leaf and pollen fossils from southern Wyoming indicate a warm temperate paleoclimate [27]. Increased warming and decreased precipitation continued through the late Cenozoic period, causing the original subtropical environment to transition to a warm temperate climate regime, gradually progressing to the arid desert conditions that presently exist in the region once covered by Lake Gosiute [28]. By then, the remains of the forests of the ancient lake shore had become petrified, protected by a blanket of younger sediments, awaiting their eventual discovery in the modern era.

4. Methods

The composition of the Blue Forest fossil woods was evaluated using a variety of laboratory methods. SEM photomicrographs were made using a Tescan Vega SEM at Western Washington University, using fractured specimens mounted on 1 cm diameter aluminum mounts using an epoxy adhesive, and sputter-coated with Pd. The mineral composition of the fossil woods was confirmed using the major element analysis obtained from the SEM samples using an EDAX energy-dispersive spectrometer. Optical photomicrographs were made using a Zeiss petrographic microscope equipped with a 5-megapixel digital camera. The density of the fossil wood and percent relict organic matter were calculated using a previously described method [29]. This technique determines the relict organic matter based on the weight loss of the powdered fossil wood following heating at 450 °C. The percentage of preserved organic matter is calculated relative to the estimated density of the wood prior to mineralization, based on the densities of the modern wood genera. The calcium carbonate content of the fossil wood and stromatolite were determined by measuring the amount of carbon dioxide released when the powdered specimens react with HCl in a sealed chamber [30]. Trace elements were measured using an Agilent 7500ce ICP-MS spectrometer with a New Wave UP213 laser ablation system at the Western Washington University Advanced Materials Science and Engineering Center. The following elements and mass numbers were analyzed: Ti (48), V (51), Cr (52), Mn (55), Fe (56), Co (59), Ni (60), and U (238). These elements were selected because they are the most common pigments for determining mineral color. Laser beam diameter was 55 micrometers, with the light output set at 55% of the full power. Six 2-mm long parallel lines were laser-etched on the sample surface. For each laser line, the data were collected as 15 replicate measurements for each element. The data were averaged, applying background corrections on the data from the blank samples. The PPM concentrations were calculated using the U.S. Institute of Standards and Technology glass reference samples, NIST 610 and NIST 614, for calibration. The results were calculated using Microsoft Excel.

5. Previous Studies

Because of the interfingering nature of stratigraphic members, lack of continuous outcrop exposure, and scarcity of stratigraphic marker beds, the correlation between various fossil wood localities is somewhat uncertain. However, at some localities that have a clearly evident stratigraphy, the silicified wood is preserved at multiple levels. Examples include Bridger Formation exposures at Oregon Buttes, representing a 203 m stratigraphic section. Tree stumps are preserved in an upright position in a 1.5 m-thick claystone bed that lies just above the contact with the underlying Green River Formation Laney Shale Member. The younger Bridger Formation strata include a 32-m thick siltstone/claystone sequence that preserves the in situ stumps, and a 0.6 m stratum that contains stromatolite-coated fossil wood [6]. This stratigraphic distribution of fossil wood was recognized as evidence that the preservation of ancient wood resulted from repeated episodes of transgression and regression of the ancient lake, not a single event.

Green River Formation fossils have been known to geoscientists from as early as the late 1800s. By the 1930s, petrified wood enthusiasts were searching Lake Gosiute localities, but the first serious study dates to 1954, when Kruse [31] described 11 new species of angiosperm wood from specimens collected at the Hays Ranch locality, in northern Eden Valley (Figures 2 and 3, location 5). Subsequent investigations have also focused on the fossil woods from the northern part of the Green River basin, near the contact of the upper Green River and lower Bridger Formations. The most-studied localities are near Big Sandy Reservoir (Figures 2 and 3, location 1). Silicified palm trunk (*Palmoxylon*) is a common floral element, comprising three species [32,33]. More recent studies of the Big Sandy Reservoir revealed four angiosperm taxa in addition to a single species of *Palmoxylon* [34]. A greater floral diversity was observed at a slightly older site at Parnell Draw (Figures 2 and 3, location 4), where 17 taxa were recognized, including both conifers and angiosperms [35]. These studies provide insights for understanding the middle Eocene plant communities that bordered Lake Gosiute. The abundance of palm trunk tissue, and the presence of dicotyledonous woods with subtropical affinities are evidence of a warm paleoclimate in central Wyoming during the late Early Eocene [34]. The deposition of the Green River basin Eocene rocks has long been recognized as occurring during warm temperate, subtropical, and tropical climate conditions [3]. The palynology of early Eocene samples suggests a humid subtropical to warm temperate climate, with summer rainfall and only mild frost, with an estimated mean temperature of 12.8 °C (55·F) [27]. Alternately, the climate of the basin floor during this time may have been frost-free [36].

The paleoflora of the Blue Forest deposit has not been studied in detail, but the general characteristics suggest that the habitat conditions were somewhat different from the above-mentioned locations. Palms appear to have been absent, conifers were rare, and angiosperms had a low diversity. Many specimens were *Schinoxylon* or Edenoxylon. Both genera are considered members of the Anacardaceae (Cashew) Family. Other taxa include various unidentified dicots and a conifer. The taxa reported from various sites in the Eden Valley area are listed in Table 1. These data are included to provide a regional paleobotanical overview, because of the scarcity of taxonomic information for Blue Forest specimens.

Table 1. Known plant taxa from southwestern Wyoming localities.

LOCATION	FAMILY	REFERENCE
HAY'S RANCH: SE of Big Sandy Reservoir		
Myrica scalariforme	Myricaceae	[31]
Talauma multiperforata	Lauracea	[31]
Forchammerioxylon scleroticum	Capparidaceae	[31]
Amridoxylon ordinatum	Rutaceae	[31]
Fagara monophlloides	Rutaceae	[31]
Fagara biseriata	Rutaceae	[31]
Suriana inordinata	Simaroubaceae	[31]
Heveoxylon microsporosum	Euphoribiaceae	[31]
Schinoxylon actinoporosum	Anacardiaceae	[31]
Edenoxylon paviareolatum	Anacardiaceae	[31]
Aspidospermoxylon uniseriatum	Apocynaceae	[31]
BIG SANDY RESERVOIR UF327: NE of Big Sandy Reservoir		
Palmoxylon macginitiei	Arecaceae (Palmae)	[32]
Palmoxylon contortum	Arecaceae (Palmae)	[33]
Palmoxylon colei	Arecaceae (Palmae)	[33]
Palmoxylon edenense	Arecaceae (Palmae)	[33]
Edenoxylon paviareolatum	Anacardiaceae	[34,35]
Laurinoxylon stickai	Lauraceae	[34,35]
Wilsonoxylon edenense	Cancellaceae	[34,35]
PARNELL DRAW: 42 km east of Farson, WY		
Cupressinoxylon sp.	Cupressaceae	[35]
Pinus sp.	Pinaceae	[35]
Palmoxylon sp.	Arecaceae (Palmae)	[35]
Edenoxylon	Anacardiaceae	[35]
Cf. *Laurinoxylon stickai*	Lauraceae	[35]
Cf. *Mastixia* sp.	Cornaceae	[35]
Platanoxylon sp.	Platacaneae	[35]
Dicotyloxylon spp. (7 unknown taxa)	Unknown	[35]
Welkotopoxylon multiseriata	Moraceae	[37]

6. Observations

Our studies focus on the fossil wood from the Blue Forest beds that lie within the Laney Shale Member (locality 3, as shown in Figures 2 and 3). This site, which is the most popular collecting locality for amateur collectors, has received little attention from paleobotanists. The scarcity of research is the result of the following two factors: the low-angle host rocks are covered by desert soil, and the era when fossil wood could be collected from the surface is long past; specimen discovery now usually requires laborious excavation (Figure 5). An additional disadvantage is that the stratigraphic relationship of individual excavation pits is seldom known with certainty. The rewards of studying the Blue Forest site are that wood specimens display a complex mineralogy, great beauty, and have taxonomic compositions that may be dissimilar to other Lake Gosiute fossil wood locations.

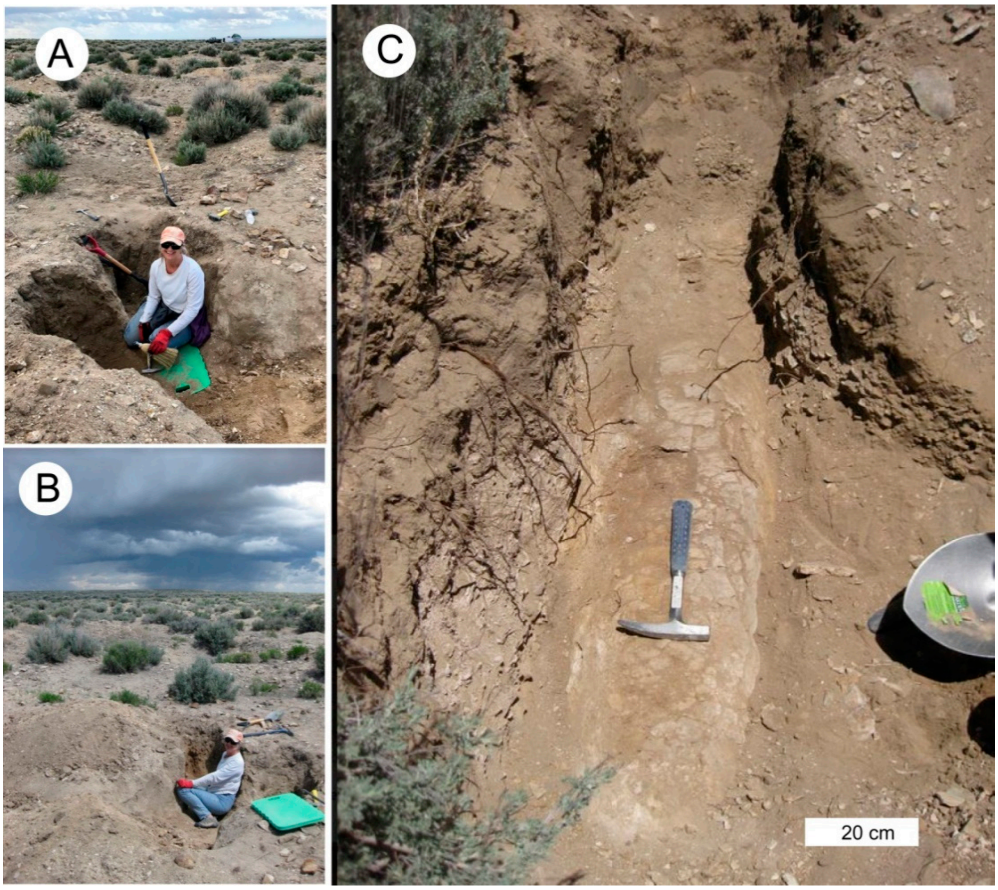

Figure 5. Blue Forest site. (**A**,**B**) Trenches excavated during 2018 field work. (**C**) Partially exposed horizontal log, showing thick stromatolitic coating. Photos by MikeViney.

6.1. Taphonomy

In the early era of specimen collecting, upright tree trunks were observed at the southwestern Wyoming sites. These fossils were particularly common in areas of pronounced topographic relief, which provide access to extended stratigraphic sequences. For example, in a 203 m stratigraphic section of the Bridger Formation at Oregon Buttes (Figures 2 and 3), upright stumps are preserved in the lowest depth of 1.5 m, and in a 32-m thick section that begins at 108 m. At 148 m above the basal contact, a 0.7 m sandy stratum contains algal-covered wood [6]. The *Palmoxylon* specimens found near Big Sandy Reservoir all came from upright stems [33]. At Blue Forest, a gentle topography and shallow inclination of bedding reduce opportunities for observing specimens in a stratigraphic context. Anecdotal reports indicate that upright trunks were discovered by early collectors at Blue Forest, but at present, intact specimens only occur in the subsurface. These fossils typically have horizontal orientations, suggesting that they represent woody debris that was submerged on the lake bottom. The common preservation of bark suggests that the wood has not been transported a long distance, as evidenced by the lack of abrasion. This taphonomy has important implications; the presence of stramatolite-coated upright trunks suggests that fossilization was related to changes in lake level that caused the inundation of a standing forest. The abundance of sub-horizontal trunks and limbs may have resulted from the toppling of dead trees, as well as the delivery of botanical debris from the adjacent watershed.

6.2. Stromatolitic Coatings

A striking characteristic of wood from southwestern Wyoming, particularly at Blue Forest, is the thick casing of biogenic calcium carbonate that surrounds silicified wood (Figures 5B, 6 and 7). These coatings commonly show stromatolitic layering, appearing to have originated when living microorganisms were subject to precipitation of calcium carbonate. Later, open spaces in the carbonate were filled with chalcedony (Figure 8). Quantitative analyses show the microbial coatings on fossil limbs consist of ~60 wt. % $CaCO_3$; no $CaCO_3$ was detected in the surrounding sandy sediment, convincing evidence that the calcareous material was of a biogenic origin, and not from later inorganic precipitation.

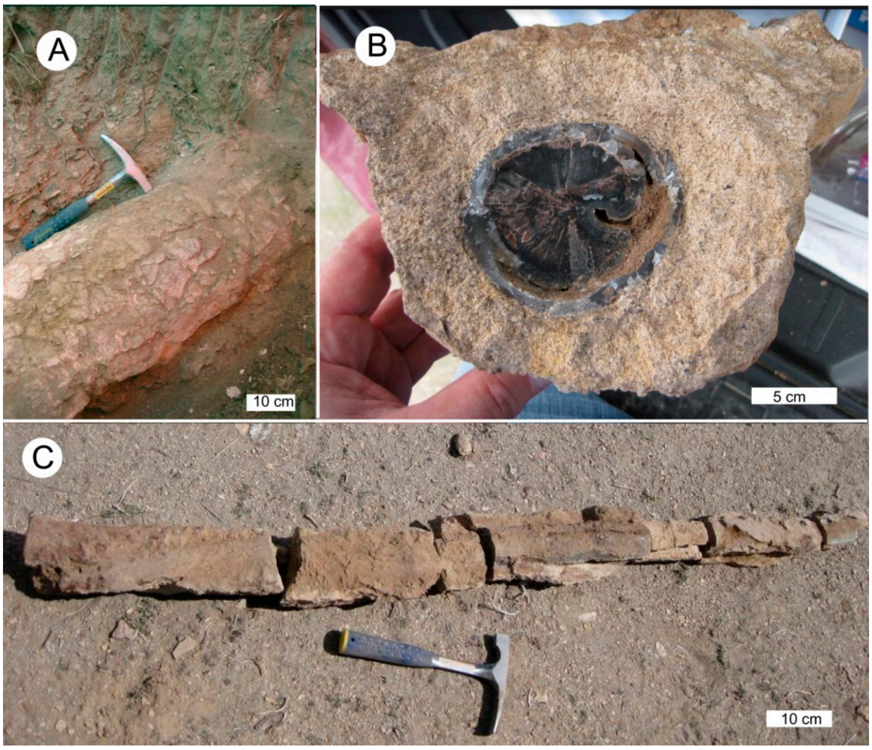

Figure 6. Freshly-excavated Blue Forest specimens. (**A**) Log coated with silicified biogenic calcareous material. (**B**) Limb surrounded by a stromatolitic layer. (**C**) Slender limb, fractured during excavation. Photos by Mike Viney, 2018.

Stromatolites are abundant in the Lake Gosiute deposits, including individual units that have a regional extent (Surdam and Wray 1976). A 1928 report [38] described "algal reefs" in the Green River Formation, noting their resemblance to the deposits made by modern cyanophytes. One unicellular microbe was identified as *Chlorellopsis coloniata*, first named for a morphologically similar fossil organism from the Miocene lakebed deposits in the Rhine graben, Germany [39]. A filamentous Green River microbe was named *Confervites mantiensis*) [38]. Bradley [38] included a photograph of wood surrounded by *C. coloniata*, but modern SEM images show that both unicellular and filamentous organisms are preserved in the carbonate layers that enclose silicified wood (Figure 9). Ostracod shells are commonly preserved in Lake Gosiute sediments, sometimes occurring in the interstices of the stromatolitic carbonate layers (Figure 10). The significance of these algal coatings is discussed later in this report.

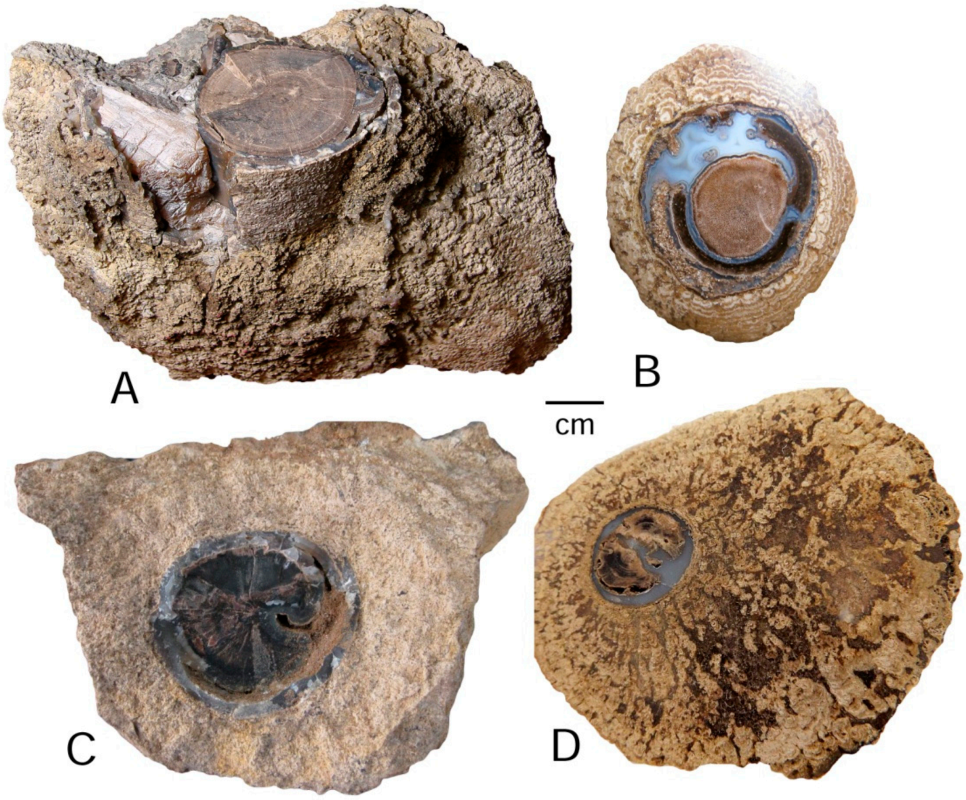

Figure 7. (**A**–**D**) Fossil limbs encased in stromatolitic coatings.

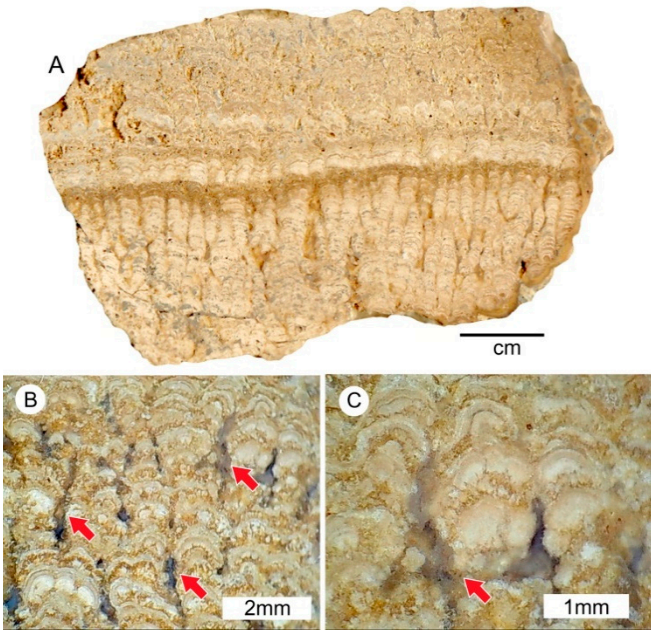

Figure 8. Calcareous stromatolites with chalcedony fillings. (**A**) general view. (**B**,**C**) Chalcedony-filled zones in are visible in magnified images.

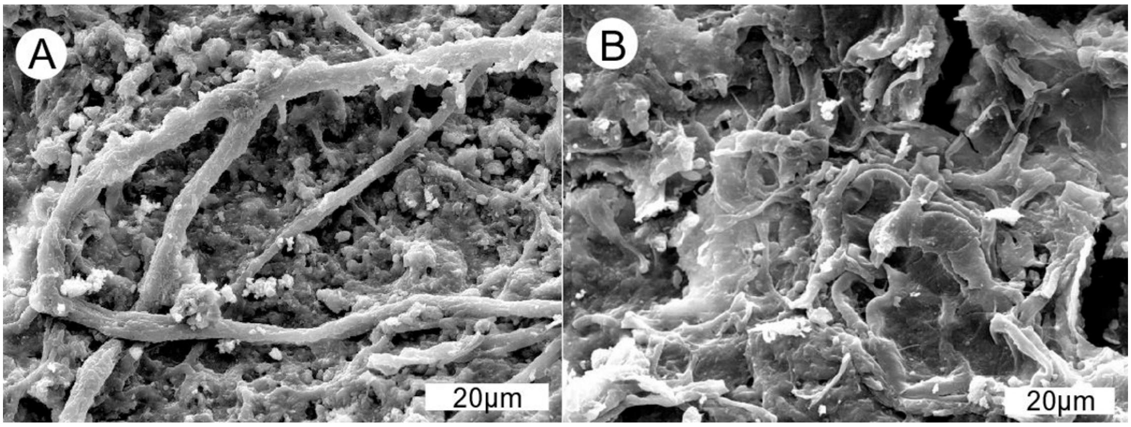

Figure 9. SEM images of silicified stromatolites, showing the presence of (**A**) filamentous and (**B**) unicellular microbes.

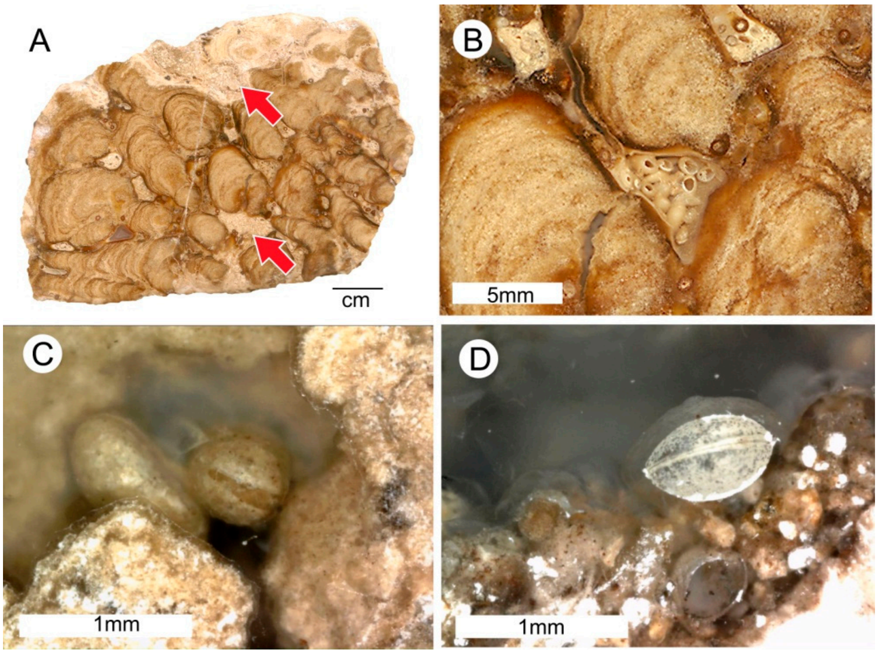

Figure 10. Ostracods in stromatolitic calcium carbonate from Lake Gosiute. (**A**,**B**) Stromatolite with ostracod valves in spaces between algal masses. (**C**,**D**) High-magnification views of individual ostracod shells.

6.3. Wood Silicification

At the Blue Forest site, fossil wood is commonly found buried at depths of about 1 m, covered by a combination of surface alluvium and silty shale. In areas where the shale is weathered, large specimens are sometimes detected using metal rods as probes; more commonly, discoveries are made by random excavations that may or may not be productive.

Fossil wood specimens range in size, from small limbs to logs with diameters of up to approximately 0.5 m. Regardless of size, fossil wood is typically enclosed within a thick rind of calcareous stromatolites. Cellular tissues are mineralized with chalcedony (Figure 11). Some specimens show visible evidence of partial degradation of the wood prior to mineralization (Figure 12). In a few instances, the wood has been almost entirely destroyed, leaving only a thin bark layer surrounding a cast of the interior wood (Figure 13). As described later, the secondary mineralization includes zones of banded chalcedony and sparry calcite.

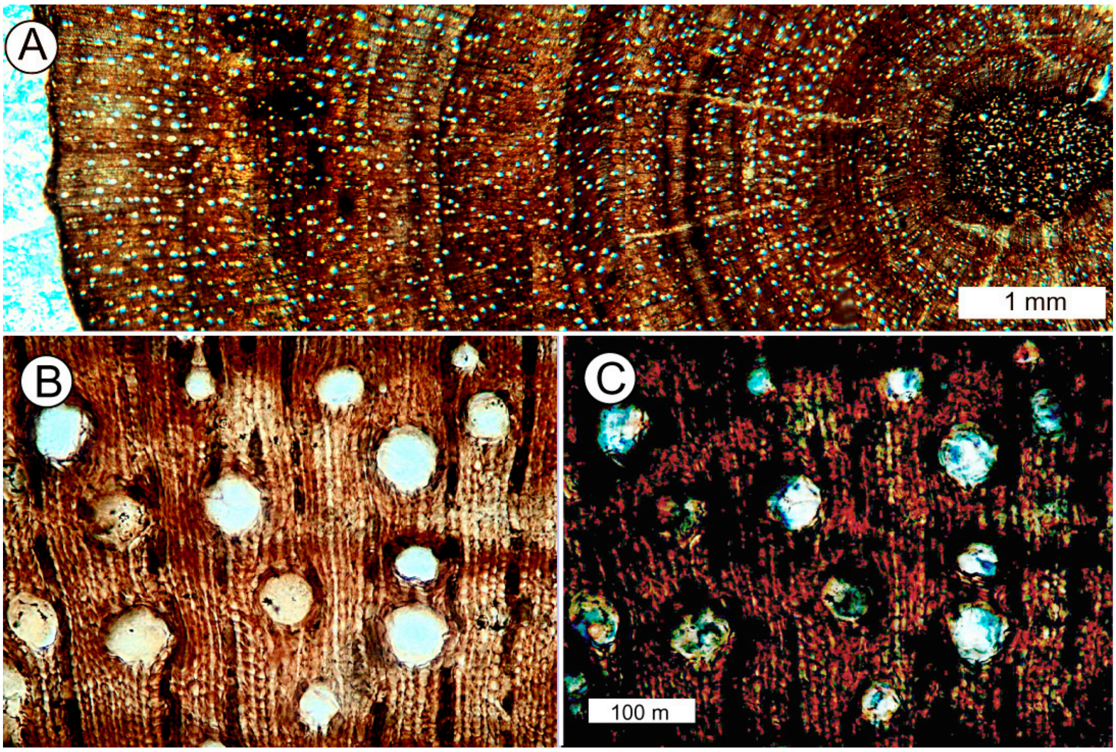

Figure 11. Thin section showing well-preserved dicotyledenous angiosperm wood. (**A**) Transverse section showing annual rings and abundant vessels. (**B**) Ordinary transmitted light illumination. (**C**) Polarized light view, showing vessels filled with chalcedony.

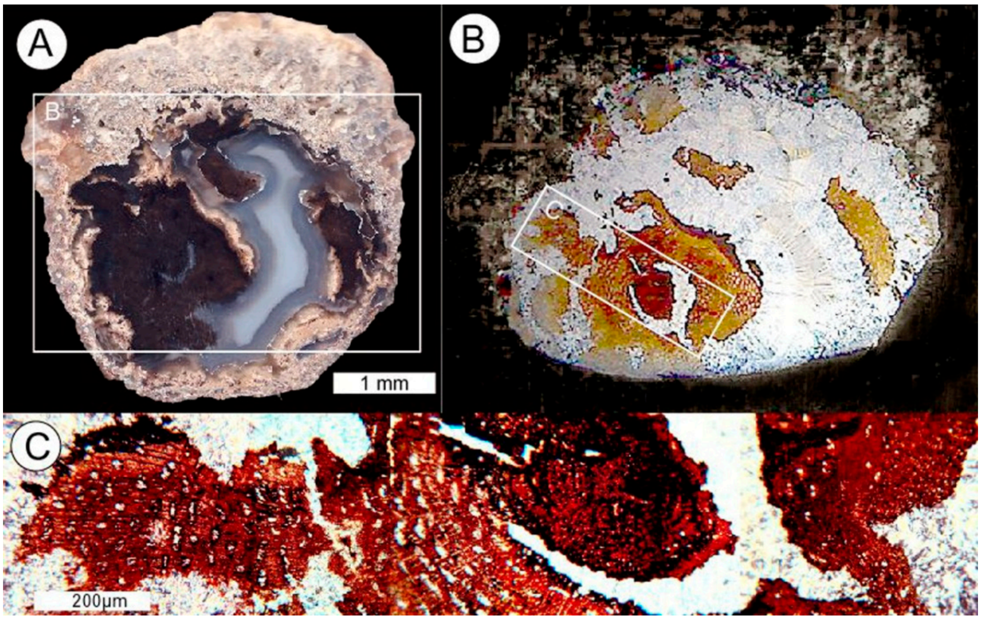

Figure 12. Fossil wood showing evidence of extensive decay prior to mineralization. (**A**) Transverse view showing silicified stromatolite coating, and a large chalcedony-filled fracture. (**B**) Transverse thin section, showing extensive chalcedony enclosing wood fragments. (**C**) Higher magnification shows the degradation of wood prior to fossilization.

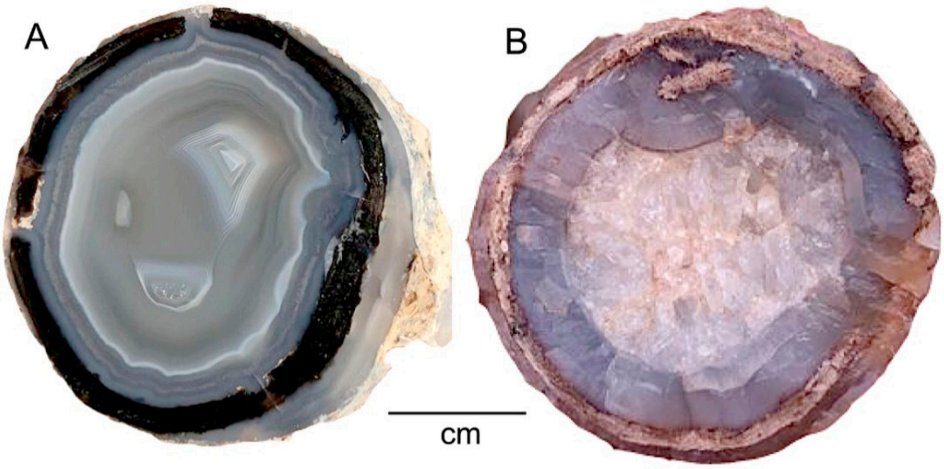

Figure 13. Eocene limb casts from southwestern Wyoming, USA. (**A**) Dark silicified bark surrounds banded chalcedony cast; Big Sandy reservoir locality. (**B**) Dark peripheral zone, inferred to be relict bark, encloses a limb cast, consisting of a thick chalcedony layer and a central area of crystalline quartz; Blue Forest locality.

SEM images show cells mineralized with chalcedony. However, a high magnification shows the material to have a sub-spherical microtexture reminiscent of opal-A lepispheres (Figure 14). This architecture suggests that chalcedony may have formed from the transformation of an opal precursor. The solid-state transformation of opal to chalcedony during wood petrifaction has previously been reported from various other sites [40–45]. Mineralization was facilitated by the porosity of the enclosing clastic sediment (Figure 15), which allowed for the flow of mineral-bearing groundwater. Abundant volcaniclastic material provided a source of soluble silica.

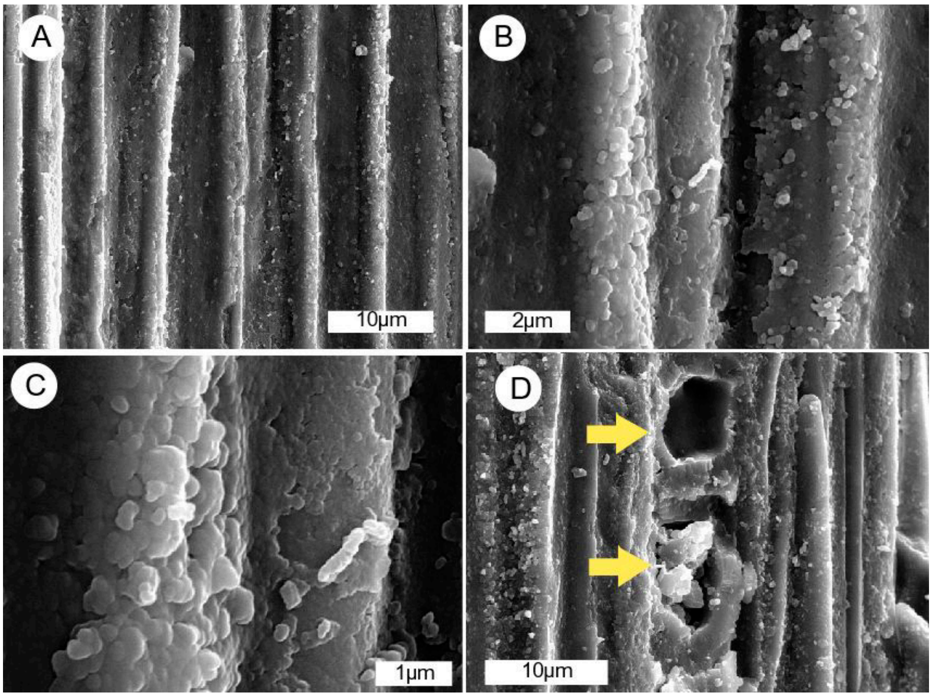

Figure 14. SEM images. (**A, B**) Longitudinal view showing silicified cells. (**C**) Chalcedony, showing relict opal lepispheres. (**D**) Tangential view, showing ray cells that are partially open (upper arrow), but with some cells containing crystalline silica (lower arrow) that precipitated during a later mineralization episode.

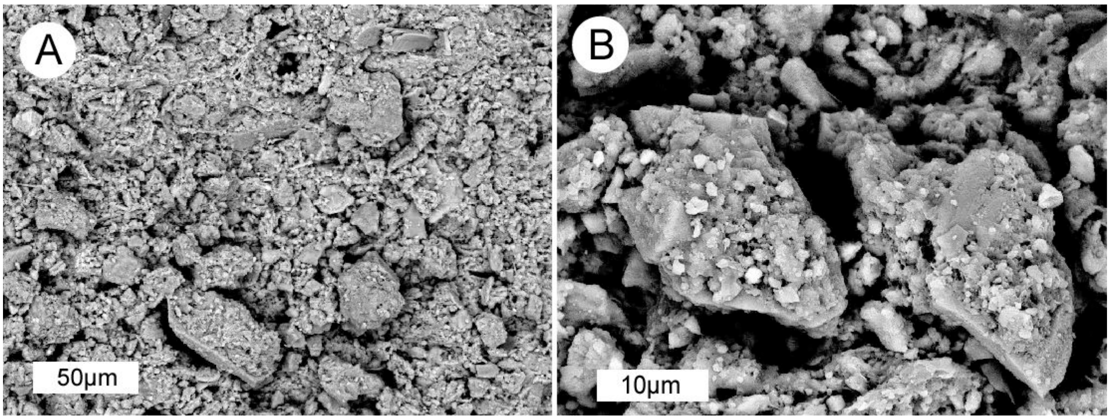

Figure 15. SEM images of siliceous silty shale. (**A**) Poorly sorted fine-grained sediment. (**B**) Note the porosity caused by interstitial spaces, and the encrustation of clast surfaces as a result of diagenesis.

6.4. Relict Organic Matter

Eocene wood from southwestern Wyoming, USA, contains relatively large amounts of relict organic matter compared with the small amounts present in most silicified wood [46]. This organic material causes a reduction in density, causing the fossil wood to retain permeability. The dark brown fossil wood readily bleaches to a lighter color, a phenomenon observable in many specimens (Figure 16). Under laboratory conditions, the bleaching can be caused by a 450 °C heating or treatment with 5% sodium hypochlorite laundry bleach. The degree of preservation of the original organic matter can be quantitatively estimated based on the weight loss after 450 °C heating, comparing the weight loss to the presumed density of the wood prior to mineralization, based on the comparative density values for modern woods. The data can be understood this way: for silicified wood that preserves 10% relict organic matter, 90% of the original wood has been destroyed during the fossilization process. Table 2 listss the data for 56 angiosperm specimens: five dicots from Blue Forest and a monocot (palm) from the northern part of the Green River Basin. In comparison, the calculated percentage of relict organic matter in the chalcedony-mineralized woods from 11 other Cenozoic sites in North America ranged from 0.65% to 9.11%, with a mean of 3.70% [46].

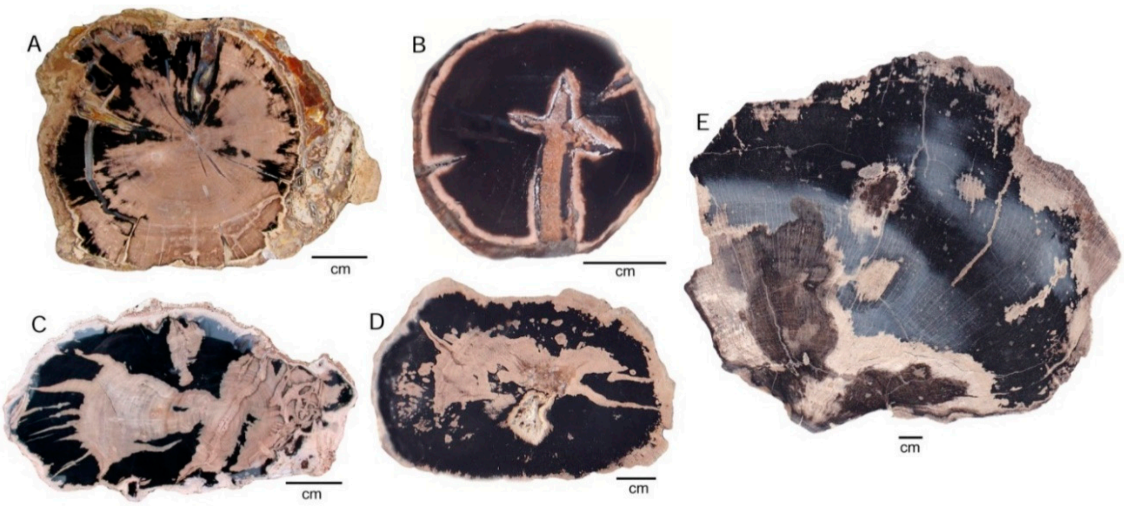

Figure 16. Bleached zones. (**A**–**E**) The dark color of the Blue Forest fossilized wood is caused by relict organic matter. In many specimens, partial bleaching was caused by the permeation of groundwater into the porous fossil wood.

Table 2. Relict organic matter.

Sample	Type	Calculated Density	LOI 450 °C	Assumed Original Wood Density	% of Original Organic Matter
BF1	*Dicot wood*	2.42	2.94%	0.60	7.1%
BF3	*Dicot wood*	2.52	4.40%	0.60	11.1%
BFTS	*Dicot wood*	2.39	6.19%	0.60	14.8%
BF2018	*Dicot Wood*	2.31	5.96%	0.60	13.8%
H3W2	*Dicot wood*	2.52	0.97%	0.60	2.4%
WP	*Palmoxylon*	2.50	1.39%	0.56	6.2%

6.5. Secondary Chalcedony

Blue Forest fossil wood originated as silicified stem tissue enclosed within a thick biogenic calcium carbonate rind, but the specimens commonly show evidence of other stages of mineral precipitation. These include spaces that contain layered or botryoidal chalcedony. This chalcedony occurs as coatings around limbs, where the outermost layers of the stem tissue (bark) adhered to the algal coating, while the inner region shrank to a smaller diameter. The resulting void is commonly filled with chalcedony (Figure 17).

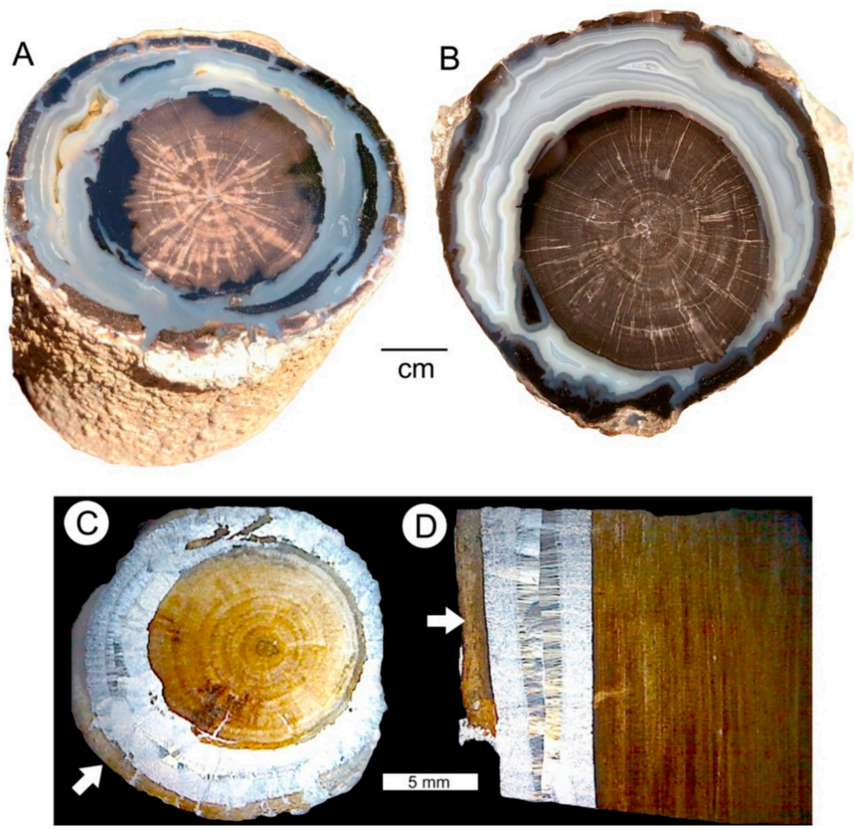

Figure 17. Secondary chalcedony. (**A**,**B**) Chalcedony filling peripheral zone caused by wood shrinkage. (**C**,**D**). Polarized light optical photomicrographs show separation of wood as a result of desiccation. Arrows show the bark layer, which remained attached to rock matrix.

Chalcedony commonly occurs in the open spaces in voids created by shrinkage prior to silicification, and in angular zones created by the brittle fracture of silicified wood. Polarized light photomicrographs show that this chalcedony was typically precipitated in multiple episodes, producing multi-layered structures (Figure 18).

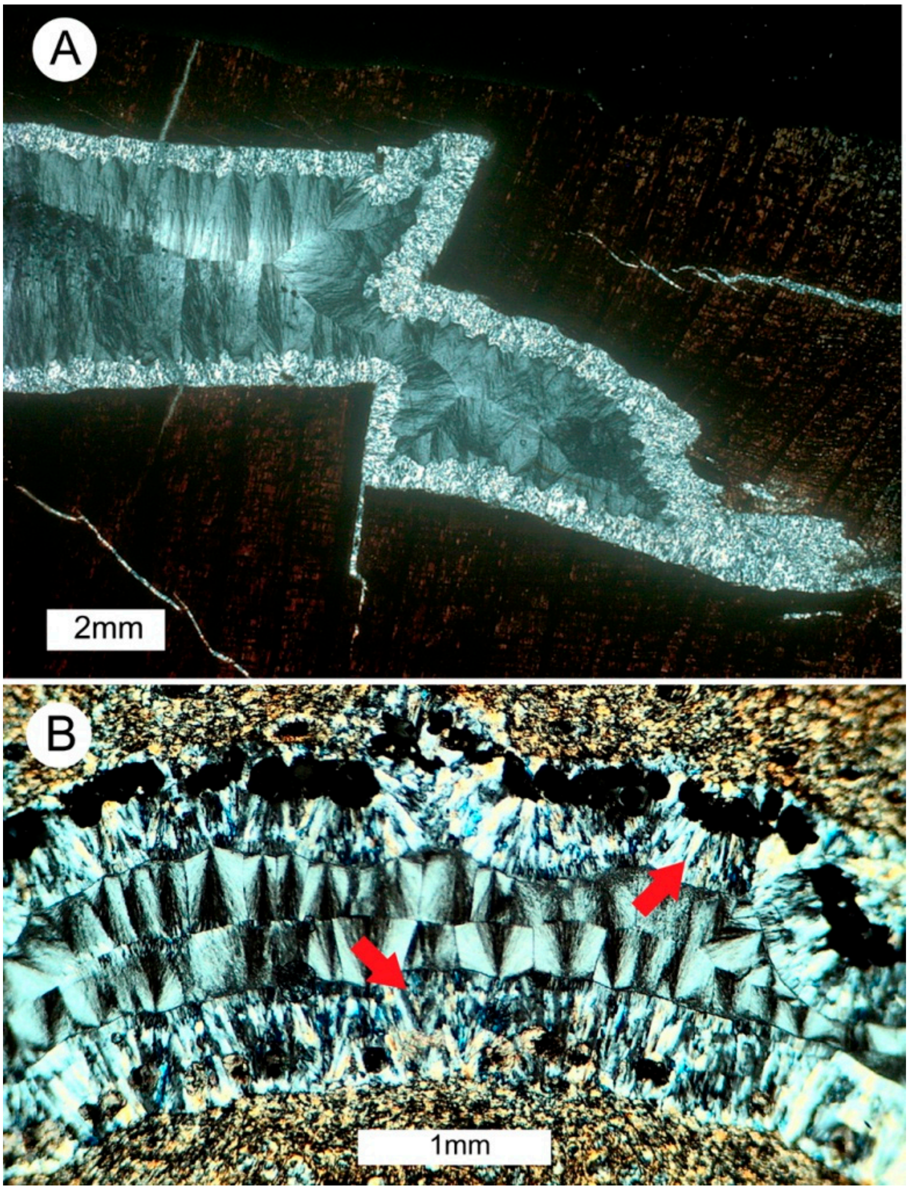

Figure 18. Polarized light optical photomicrographs of chalcedony in fractures. (**A**) Two layers of chalcedony fill an angular fracture. (**B**) In this shrinkage zone, the outer chalcedony layer shows a botryoidal form (arrows), the inner zone consist of polygonal sectors with a radiating fibrous structure.

Chalcedony also commonly fills large fractures and decayed areas (Figure 19).

6.6. Crystalline Quartz

Chalcedony is the most common material filling fractures and voids, but crystalline quartz is present in some specimens. These quartz crystals were typically deposited on cavities that are lined with a layer of chalcedony (Figure 20). This morphology may be evidence of multiple silica precipitation events; the rapid deposition of chalcedony from groundwater that contained relatively high levels of dissolved silica, and a later precipitation event when low levels of dissolved silica allowed for well-ordered crystals to develop at a slow rate. This phenomenon has been described for fossil wood from other locations [44].

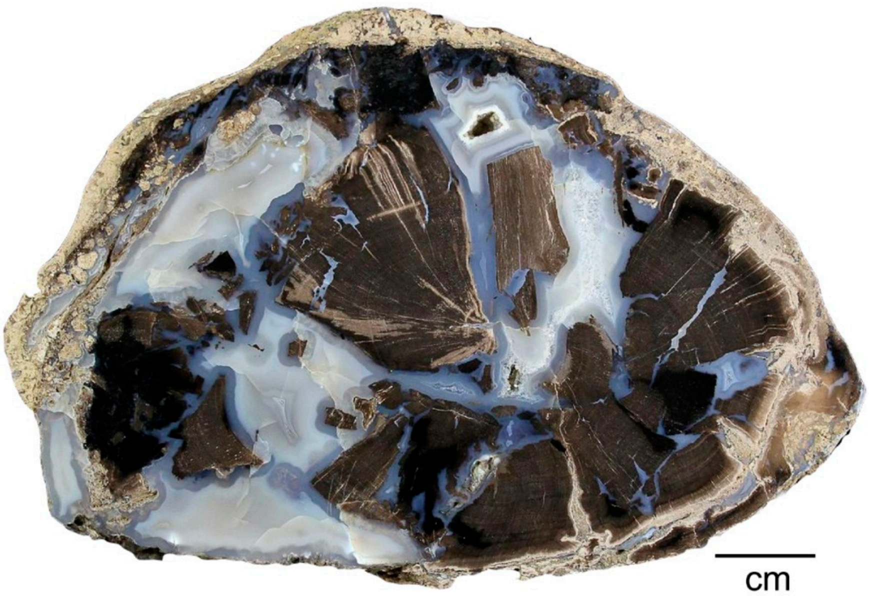

Figure 19. Banded chalcedony filling shrinkage cracks and decayed areas in a Blue Forest limb.

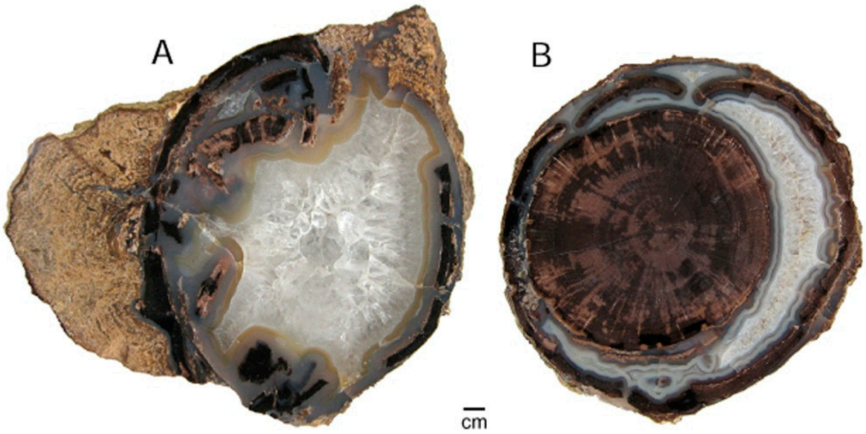

Figure 20. Coarsely-crystalline quartz fills large voids in some Blue Forest specimens. (**A**) Quartz filling interior spaces in decayed wood. (**B**) Quartz was also precipitated in the peripheral spaces, where thin layers of chalcedony provide a substrate.

6.7. Crystalline Calcite

The presence of coarsely-crystalline calcite is a striking characteristic of Blue Forest fossil wood (Figure 21). The mineral occurs as a filling material for large void spaces. Calcite commonly occurs as an over-coating on chalcedony layers, but chalcedony has not been deposited on calcite. These characteristics suggest that calcite precipitation represents the final stage of mineralization. Evidence supporting this multistage mineralization includes specimens that have been extensively silicified, but still contain open regions that could later be sites for the precipitation of calcite or quartz crystals (Figure 22). The only requirement would be the existence of a crack or porosity that would allow for an influx of mineral-bearing groundwater.

Calcite is often dissolved by amateur collectors, because they seek to show the maximum amount of the blue chalcedony in their finished polished display specimens. Experience has taught them that the elimination of the yellow sparry calcite will often reveal the underlying botryoidal chalcedony, a feature felt by many collectors to be superior to the color contrast provided by the original calcite infilling of the cavity. Thus, yellow calcite is not seen in collections as often as it may have occurred in the original specimens.

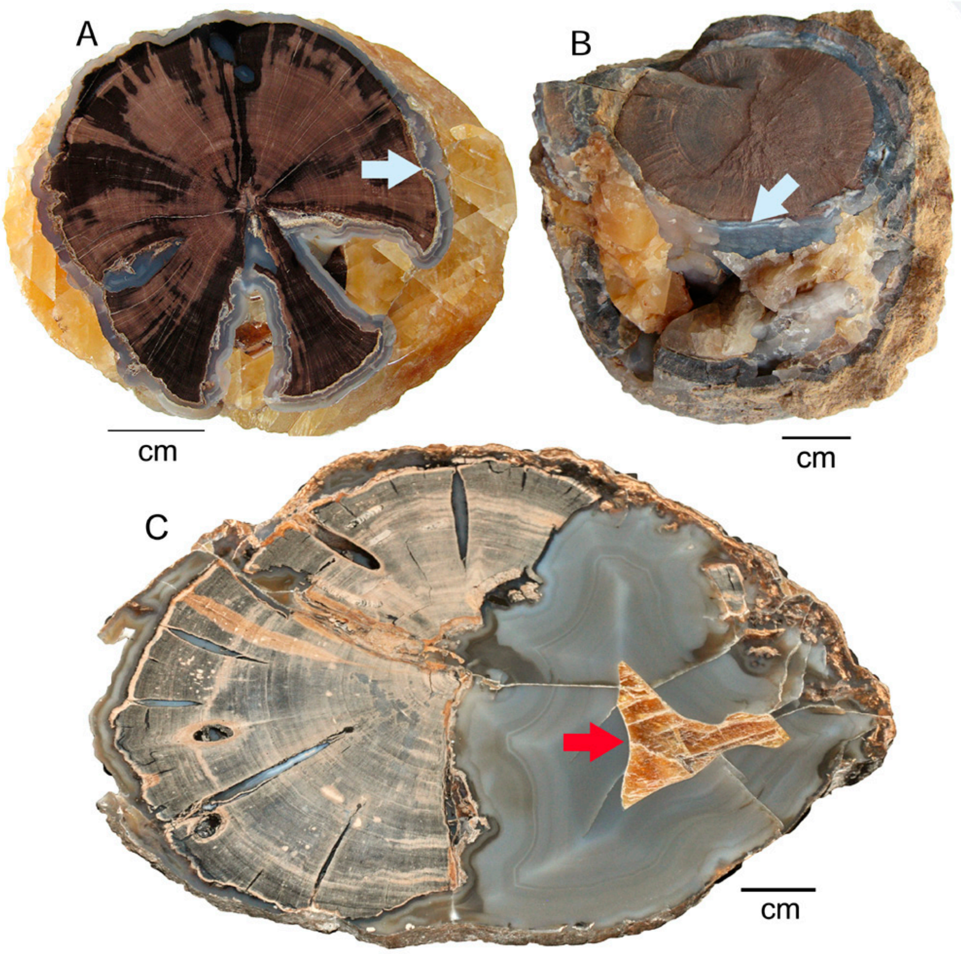

Figure 21. Yellow calcite crystals occur in void spaces within the Blue Forest fossilized limbs, and in the perimeter zones. (**A**,**B**) Calcite overlays thin chalcedony (blue arrows). (**C**) Unidentified dicot wood with large area of banded chalcedony enclosing calcite (red arrow).

Figure 22. Blue Forest limb cast containing a large central void, a potential site for the future precipitation of calcite or quartz crystals.

6.8. Trace Element Geochemistry

Trace elements determinations were performed for Blue Forest materials that included calcite, chalcedony, and two fossil woods Table 3. The significance of these data is considered in the Discussion section.

Table 3. Trace elements in Blue Forest geologic materials (PPM).

Sample	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	U
calcite	4	2	1	7545	458	3	2	4	0
chalcedony	47	28	34	186	1087	3	6	54	1
wood #1	17	768	22	105	461	1	1	12	3
wood #2	133	699	22	171	675	2	1	25	4

7. Discussion

The complex mineralization of the Lake Gosiute fossil wood specimens is as a result of the environmental changes in the ancient lake basin, combined with subsequent diagenetic processes. The abundance of fossil wood specimens is evidence of the lakeside forests that flourished during the early Eocene. As noted above, taxonomic compositions vary among the various collecting localities, indicating that the ancient plant communities were controlled by local habitat conditions. These variations may be related to small differences in geologic age, because Lake Gosiute was experiencing rapid rates of change as a result of climate, volcanic activity, and tectonism. However, several generalizations can be made. The Green River paleofloras are typically subtropical in character, as evidenced by the abundant palm fossils, as well as the affinities of many dicotyledenous taxa with plants that currently inhabit warm, wet environments.

7.1. Fossilization Processes

The occurrence of fossil wood at multiple stratigraphic levels in the well-exposed strata at Oregon Buttes [6] is evidence that the conditions required for wood petrifaction existed multiple times during the history of Lake Gosiute. This interpretation is supported by the differing stratigraphic positions of other Eden Valley fossil wood occurrences (Figure 3). For these sites, a preliminary step in the fossilization process was the development of lakeside forests. The existence of abundant plant life is easy to explain, given the subtropical climate and fertile volcaniclastic-rich soils.

The lack of surface bedrock exposure at Blue Forest limits stratigraphic observations. However, Eocene fossil wood occurrences at other southwestern Wyoming locations include in situ stumps enclosed within lacustrine sediments, clear evidence that rising lake waters produced drowned forests. This interpretation is supported by the thick coatings of calcareous stromatolite that occur on almost every specimen. Modern lakes provide analogs for this phenomenon. In his pioneering studies on Green River Formation algal reefs, Bradley [38,45] compared the deposits to the modern biogenic calcium carbonate deposition at Green Lake, New York, USA, where coatings form on fallen trees along the lake shore. This mineral precipitation occurs in association with cyanophytes (formerly known as "blue-green algae"), which grow in lake water saturated with calcium carbonate [46,47]. Ancient examples include Miocene and Pleistocene microbial travertines in southern Germany [48], and an Upper Jurassic fossil forest at Lulworth Cove in southern England. The latter example consists of upright tree trunks that were entombed in calcareous stromatolites in a shallow hypersaline marine basin [49]. The general aspects of the calcium carbonate deposition in aqueous environments were reviewed in 1996 [50]. At Gosiute Lake, regionally significant stromatolitic carbonate deposits have thicknesses that range from 1.5 to 15 m, including nine to twelve units within the Laney Shale Member, the stratigraphic host for the Blue Forest. The stromatolite deposition has been interpreted as resulting from a rise in the lake level along a shoreline where the topographic gradient was only 16–33 cm/km [51]. At a low gradient, a small transgressive event could potentially produce an extensive area of drowned forest, where trees are killed by having their roots immersed in alkaline water.

The thick microbial coatings are evidence that the trees and fallen branches became entombed in a protective calcareous layer prior to wood petrifaction. However, this mineralization appears to have occurred following the regression of the lake level, exposing the organic material to subaerial conditions. This interpretation is based on the desiccation features observed in many Blue Forest specimens. These features include tissue shrinkage, which produced extensive radial fractures, and empty spaces along the peripheries of many specimens (Figures 17–19). Areas of tissue decay also suggest subaerial exposure, which facilitates fungal degradation.

7.2. Sequential Mineralization

7.2.1. Step 1: Wood Silicification

Mineralization began after the desiccated algal-coated wood was buried in clastic sediment. The permeability of the algal carbonate allowed for the penetration of silica-bearing groundwater. The silty sediment was likely a product of fluvial transport; the abundance of volcaniclastic material provided a ready source of soluble silica. As noted previously (Figure 9), the initial silica precipitation may have been in the form amorphous opal (opal-A); the present chalcedony composition is presumably the result of a diagentic transformation.

7.2.2. Step 2: Secondary Chalcedony

Botryoidal or banded chalcedony that occupies large internal zones, or in the form of peripheral layers, represents a later stage of mineralization. This chalcedony, which occurs as banded layers and as botryoidal coatings, appears to have originated as a primary precipitate that formed after the cellular tissue was already silicified. This episodic style of mineralization may have been caused by fluctuations in the water table, which, in a shallow basin, would have been primarily controlled by fluctuations in the lake level. The silicification of interstitial spaces in the calcareous stromatolites (Figure 9) may have occurred at this time.

7.2.3. Step 3: Calcite Crystallization

The final stage in wood petrifaction occurred when crystalline calcite was deposited in the remaining open spaces. The formation of this calcite presumable represents a slow rate of precipitation, allowing time for the development of relatively large crystals. Evaporative carbonate precipitation was particularly likely in the mudflats bordering the lake, where the sediments were saturated with saline/alkaline lake water [22]. The switch from silicification to calcite precipitation in the wood may have been as a result of changing geochemical gradients; the conditions favoring the precipitation of the two elements are related to pH (Figure 23). The chemical conditions may have been highly localized, related to the unique environment of the wood as it simultaneously experienced degradation and preservation. The loss of >85% of the original organic matter (Table 2) is evidence of degradation that may have produced pH and Eh gradients during the process of mineralization; the detailed preservation of cellular morphology is evidence that this tissue loss occurred at a gradual rate, which allowed for the anatomical features to be replicated by silica. The absence of secondary calcite or chalcedony in the silty matrix demonstrates that the precipitation of both minerals was limited to the entombed wood.

Sawn specimens show channels that were conduits for the entry of silica-bearing solutions from an external source, resulting in the precipitation of chalcedony in peripheral spaces and interior zones. Crystalline calcite occupies chalcedony-lined voids (Figure 24).

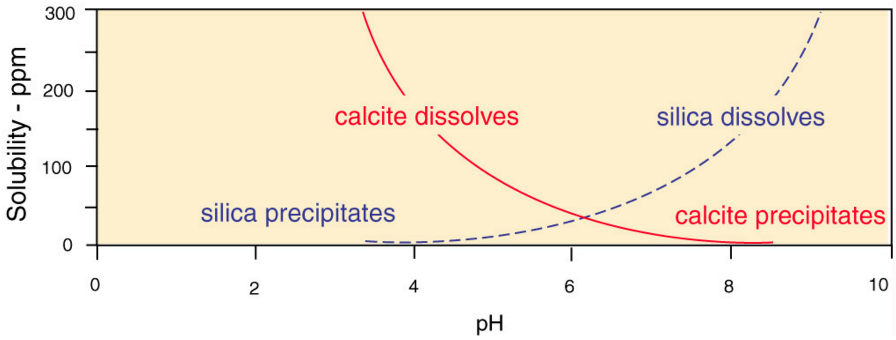

Figure 23. Solubility of calcite and silica at 25 °C. Data adapted from [52,53]. Reprinted from [54].

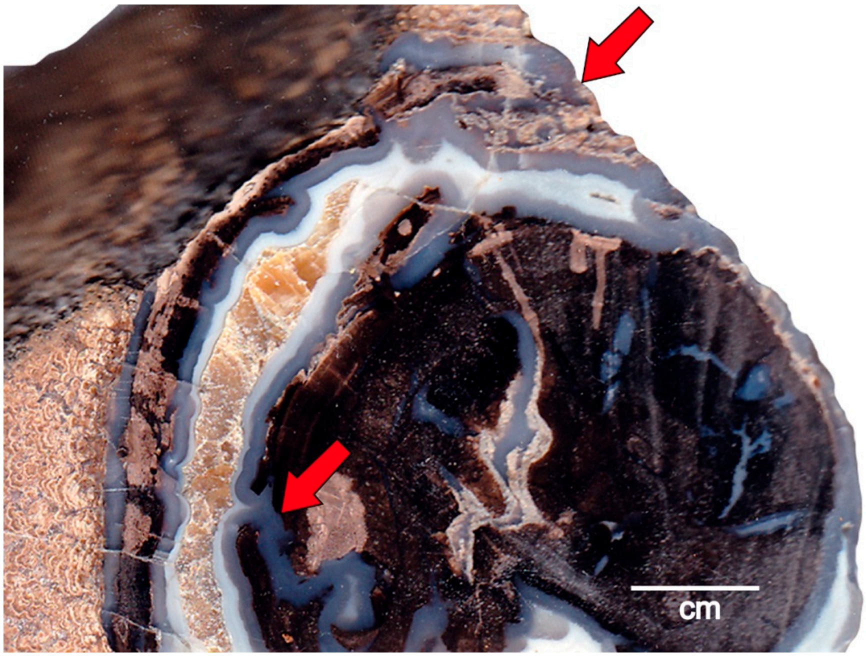

Figure 24. Transverse section of fossil wood, showing sinuous chalcedony-filled channels (arrows), and sparry calcite filling a crescent-shape peripheral zone.

7.2.4. Step 4: Quartz Crystallization

Like calcite, zones of clear quartz crystals developed in the spaces that remained open during the earlier stages of mineralization (Figures 21 and 23). The formation of quartz rather than chalcedony likely occurred as a result of lower levels of dissolved Si in groundwater, resulting in slower precipitation rates, which provided time for the silica to develop a well-ordered lattice structure. Similar mineral transitions are common in geodes, where crystal-lined central cavities have developed on layered chalcedony substrates [41].

Not every specimen exhibits the full mineralization sequence. Secondary chalcedony is ubiquitous, calcite crystals are common, and zones of quartz crystals are observed less frequently. When present, the combination of all of the mineralization phases may produce specimens of a great complexity (Figure 25).

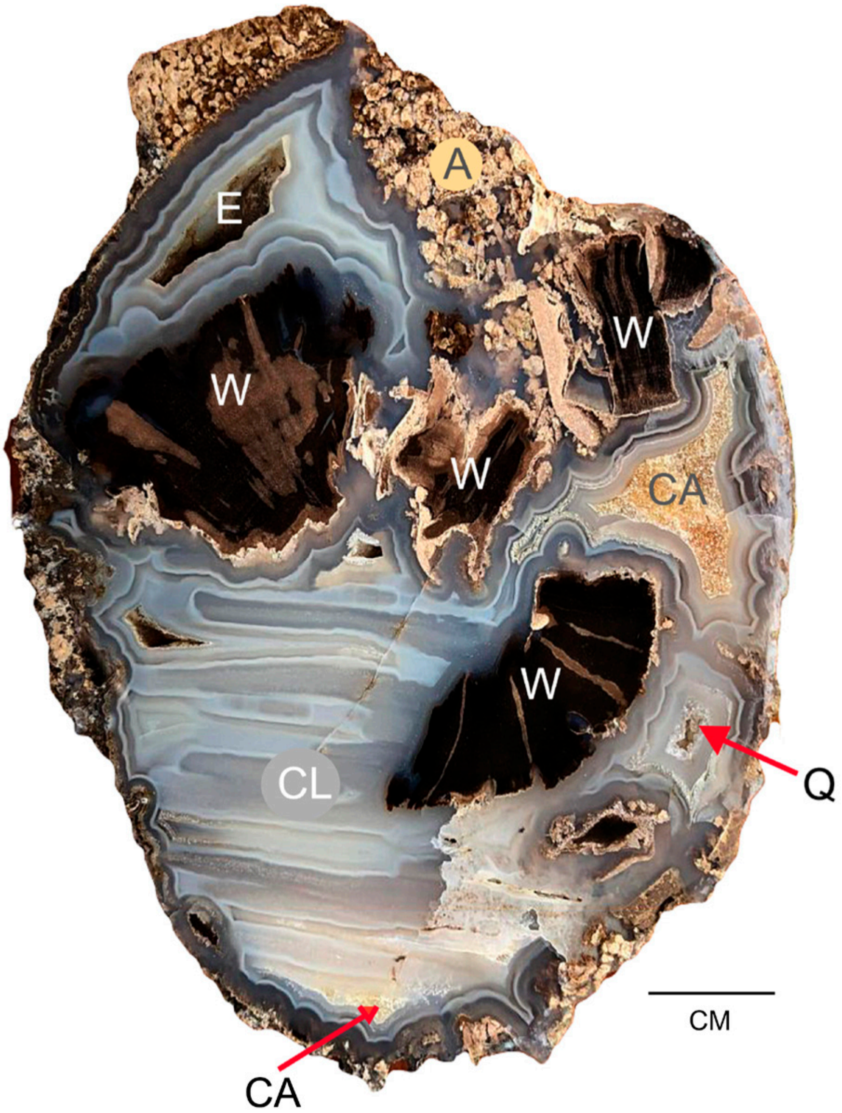

Figure 25. Blue Forest slab containing multiple mineral phases. A = algal coating; CA = calcite; CL = chalcedony; E = empty space; W = silicified wood; Q = quartz.

7.3. Evidence from Trace Elements

Trace element abundances provide evidence for the origin of color of the mineral phases, and for the multiple-stage mineralization processes. Crystalline calcite in the Blue Forest specimens ranges from yellow to yellowish orange in color. Analyses of a typical sample reveal that the color is likely to be caused by elevated levels of manganese, with iron also playing a role (Table 3). Manganese commonly occurs in association with calcite (e.g., manganoan calcite). These specimens are typically light pink [55], suggesting that the yellowish color of the Blue Forest calcite is influenced by the presence of Fe. Translucent blue-gray chalcedony perhaps owes its color to optical effects, but elevated levels of Fe suggest that this element may be a pigment. The colors produced by iron are determined by the oxidation state and elemental abundance, but a wide range of colors may be produced [56]. As noted above, relict organic matter may be a cause of the dark brown color of the silicified wood. However, elevated levels of V, Mn, Fe, and Ti (for sample 2) suggest that these trace elements may contribute to the color. However, the susceptibility of bleaching of the fossil wood suggests that relict organic matter is the most important pigment.

The trace element variations support multiple episodes of mineralization. The initial silicification of wood tissue involved silica-bearing groundwater that also contained Ti, V, Mn, and Fe. In contrast, the V levels were low in the solutions that later produced chalcedony. This element is likewise low in the groundwater associated with calcite precipitation, but the levels of dissolved Mn and Fe were high. The presence of trace elements in fossil wood has received relatively little attention, but modern instrumental methods greatly facilitate a rapid and accurate determination of these constituents. Our data suggest the value of trace elements for interpreting mineralization conditions.

8. Conclusions

The Eocene lacustrine strata of southwestern Wyoming have preserved the abundant vertebrate fossils that have been the subject of much research. In comparison, fossil wood is highly prized by fossil collectors, but the geologic processes responsible for the preservation of these fossils have received little attention. The same can be said for many fossil wood localities, where research has commonly been focused on taxonomy and paleoecology. Blue Forest, Wyoming, USA, is an example of a site where fossil wood has a complex mineralogy that resulted from multiple geologic events, ranging from changes in the lake levels that affected lakeside forests, to multiple stages of mineral precipitation during diagenesis. Many questions remain to be answered, particularly in regard to the paleobotanical aspects of the fossil wood. The significance of our work is the demonstration that complex fossilization processes can be interpreted using geologic information in combination with the standard methods of microcopy and geochemistry.

Author Contributions: M.V. initiated this project, performed the field work, and provided most of the research specimens. J.M. contributed information based on his earlier visits to the site. Both coauthors provided photographs and participated in the writing and editing of the manuscript. G.E.M. contributed analytical data and wrote the first draft.

Funding: This research received no external funding.

Acknowledgments: We thank Nareerat Boonchai and Steven Manchester, from the Florida Museum of Natural History, for sharing their knowledge of Eocene woods from Wyoming, USA. Kyle Mikkelsen provided technical assistance for trace element analysis. Mary Klass participated in field work.

Conflicts of Interest: The authors declare no conflict of interest

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