Fossil wood in the upper Santa Fe Group, south-central New Mexico: implications for mineralization style and paragenesis

Jochems, Andrew P. Hobbs, Kevin M. and George E. Mustoe

2022, pp. 295-304. https://doi.org/10.56577/FFC-72.295

in:

Socorro Region III, Koning, Daniel J.; Hobbs, Kevin J.; Phillips, Fred M.; Nelson, W. John; Cather, Steven M.; Jakle, Anne C.; Van Der Werff, Brittney, New Mexico Geological Society 72nd Annual Fall Field Conference Guidebook, 426 p. https://doi.org/10.56577/FFC-72

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 72nd Fall Field Conference, 2022, p. 295–304.

FOSSIL WOOD IN THE UPPER SANTA FE GROUP, SOUTH-CENTRAL NEW MEXICO: IMPLICATIONS FOR MINERALIZATION STYLE AND PARAGENESIS

ANDREW P. JOCHEMS[1], KEVIN M. HOBBS[1], AND GEORGE E. MUSTOE[2]

[1]New Mexico Bureau of Geology and Mineral Resources, Socorro, NM 87801; andy.jochems@nmt.edu
[2]Geology Department, Western Washington University, Bellingham, WA 98225

Abstract—Fossilized wood is known from New Mexico strata spanning the Pennsylvanian through Quaternary, but few systematic studies have been conducted to document petrifaction style, timing/sequence, and mineral assemblages. Plio-Pleistocene deposits of the upper Santa Fe Group in south-central New Mexico contain fossil angiosperm wood that has undergone silicification or calcification, the two most common modes of wood petrifaction. Fossil wood occurs in axial-fluvial sediments deposited by the ancestral Rio Grande between ~3.6 and 0.8 Ma. X-ray diffraction (XRD) patterns and petrographic analyses were used to assess calcified and silicified specimens from the Camp Rice Formation (upper Pliocene) in the Hatch-Rincon Basin, and silicified specimens from the Palomas Formation (lower Pleistocene) in the San Marcial Basin. Opalized wood from the Camp Rice Formation is mineralized with both disordered cristobalite and tridymite (opal-CT) and chalcedony, whereas Palomas Formation samples are dominated by crystalline quartz. Preserved anatomical structures agree with longstanding models of initial silicification on wood cell walls, but the age of the deposits in which the specimens were found and co-occurrence of opal-CT and chalcedony challenge paradigms regarding fossil wood age and genetic sequence. Future research should address silica sources in the Camp Rice and Palomas formations and seek to constrain the timing of mineralization.

INTRODUCTION

Fossil wood specimens are known from a range of Phanerozoic rocks in New Mexico and have been used to infer depositional settings (Elrick et al., 2017), paleoclimate (Wheeler et al., 1995; Hudson and Boucher, 2006; Falcon-Lang et al., 2016), mineralization characteristics (Sweeney et al., 2009), and paleobotanical context (Brues, 1936; Estrada-Ruiz et al., 2012, 2018). However, occurrences of mineralized wood from younger rocks are sparse and generally reported in an ancillary manner to better known vertebrate fossil assemblages from Neogene-Quaternary strata (e.g., Kues and Lucas, 1979). Northrop (1962) mentions opalized wood “at various localities in the Santa Fe formation of the Rio Grande Valley and Jornada del Muerto, notably near the north end of the Fra Cristobal Range north of the Caballo Mountains and south of San Marcial,” but gives no stratigraphic or geographic context. In the same publication, Northrop (1962) references “opalized wood of *Fraxinus* (ash) with cell structure beautifully preserved occurs in abundance near the Bernardo bridge, about halfway between Los Lunas and Socorro.” This geographic location suggests that the opalized *Fraxinus* specimens likely were derived from Santa Fe Group sediments, but again, no stratigraphic or detailed geographic context is given. Stein (1982, fig. 2) provides X-ray diffraction (XRD) data for a single sample of petrified wood from the “middle member of Santa Fe Formation, New Mexico (Pliocene),” showing dominantly opal-CT content, but gives no indication of its provenance.

The paleontological record of the Santa Fe Group is rich in fauna, but its paleobotanical records are rarer and have received little attention from researchers. Mammalian biostratigraphy within the upper Santa Fe Group, including the Camp Rice Formation and Palomas Formation, has been a crucial tool in correlating units and developing an integrated chronology of the tectonosedimentary evolution of the Rio Grande rift through the Pliocene and Pleistocene, yet little is known about the non-mammalian paleoecology of these deposits. This work reports on the discovery, identification, mineralization, and genetic processes of fossilized wood from Pliocene-Pleistocene fluvial deposits of the San Marcial and Hatch-Rincon basins, New Mexico (Fig. 1), that was discovered during geological mapping of the Arroyo Cuervo and Paraje Well 7.5-minute quadrangles.

GEOLOGIC SETTING

Fossil wood localities in the San Marcial and Hatch-Rincon basins are found in upper Pliocene and Pleistocene axial-fluvial deposits (Fig. 2; Jochems, 2017; Koning et al., 2020a) representing sedimentation associated with early phases of a paleo–Rio Grande flowing through connected (as opposed to separated) half-graben rift basins. In the Hatch-Rincon Basin, the fossil wood–bearing formation is the Camp Rice Formation. Fossil wood is found in the Palomas Formation in the San Marcial Basin. These two formations are lithologically similar and can be correlated with each other, and with the similar Sierra Ladrones Formation of the Socorro and Albuquerque basins farther north (Lozinsky and Hawley, 1986). These formations each contain coeval, lithologically-defined intrabasinal subunits which are interpreted to represent unique depositional environments (Hawley and Kottlowski, 1969; Seager et al., 1982; Lozinsky, 1986; Jochems, 2017; Koning et al., 2020a). Exact correlation of depositional timing in different basins varies and is difficult to constrain, but recent work suggests a Pliocene to lower Pleistocene onset of deposition for these

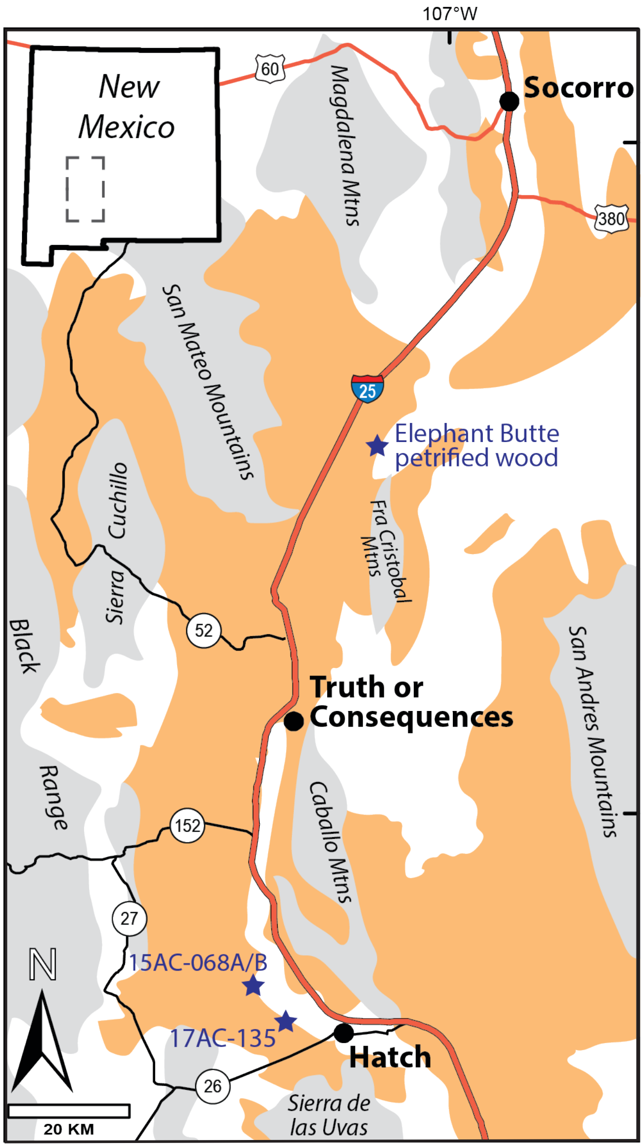

FIGURE 1. Location map for fossil wood samples collected from the upper Santa Fe Group in south-central New Mexico. Orange-brown polygons represent generalized area of upper Santa Fe Group exposure (Palomas and Camp Rice Formations). Gray polygons are mountain ranges. Stars are sample locations.

units (Leeder et al., 1996; Morgan and Lucas, 2012; Jochems, 2015). These units were deposited during an aggradational phase of Rio Grande rift history. Magnetostratigraphic data indicates that aggradation continued until approximately 0.8 Ma (Mack et al., 1993). Since then, incision into and erosional removal of Pleistocene and older sediments has dominated (Sion et al., 2020).

WOOD PETRIFACTION AND CHEMISTRY

Wood petrifaction, or the mineralization of plant tissue, has been hypothesized to occur in one of two ways: (1) replacement, by which minerals precipitate in spaces previously occupied by organic matter (Von and Correns, 1950); or (2) permineralization, where open spaces are mineralized but some cell material is left intact (St. John, 1927). "Organic templating" is considered the first step in silica permineralization due to the affinity of silicic acid for cellulose and lignin polymers in plant vascular tissue (Leo and Barghoorn, 1976). Silica deposition in the templating process initiates on porous cell walls, rather than cell or vessel lumina, promoting preservation of anatomical details. Original organic material is commonly lost to microbial or chemical attack as mineralization proceeds, and the final product of petrifaction frequently resembles replacement (Mustoe, 2017). Thus, the two mechanisms of wood petrification need not occur independently or at different times, and instead result from simultaneous processes.

Dissolved silica in wood petrifaction is commonly sourced from feldspars and volcanic glass (Matysová et al., 2010; Ballhaus et al., 2012), though Buurman (1972) observed that silica may be liberated from many rock types via soil formation. Wood is silicified in the presence of dissolved silica at low (acidic) pH values. Four forms of silica may be involved in wood petrification (Scurfield and Segnit, 1984): (1) nearly amorphous hydrous silica (opal-A); (2) disordered tridymite and cristobalite (opal-CT); (3) chalcedony; and (4) microgranular quartz, with some specimens containing chalcedony in combination with either quartz or opal.

The transformation between silica species in fossil wood is inferred from several lines of evidence, including the abundance of opalized wood of Cenozoic age relative to older Mesozoic samples where chalcedony and/or quartz mineralization predominates (Felix, 1897; Stein, 1982), and documented transformation of opal-A to opal-CT to chert in siliceous biogenic deposits and hot spring sinters (e.g., Kastner et al., 1977; Williams and Crerar, 1985; Williams et al., 1985; Herdianita et al., 2000). Opaline silicification of wood is associated with diagenesis and its transformation to other silica species may be a function of age and burial temperature (Mizutani, 1970, 1977). In any case, polymineralic samples demonstrate that mineralization is not limited to a single transformation pathway (e.g., Jefferson and Macdonald, 1981; Augustithis, 1982; Mustoe, 2008) and that an intermediary opal-CT phase is not essential (Buurman, 1972).

Calcite mineralization is the most common form of wood petrifaction after silicification and is known from numerous sites of Jurassic through Pleistocene age (Mustoe, 2018). It occurs at higher (basic) pH values than silicification, and, as a result, the two forms of petrifaction are rarely observed together even when dissolved silica is abundant. Calcification of wood occurs in cell walls but without organic templating as described above. Instead, cell walls are entombed, not replaced, by calcite and thus the process may be considered permineralization. Although calcite mineralization generally occurs under geochemical conditions favorable to preservation of anatomical elements, the expansive force of crystallization may disrupt plant tissues (McBride et al., 2003; Mustoe and Beard, 2021). Anatomical features in fossil wood can also be obliterated by normal decomposition processes (e.g., by fungi in subaerial settings), and preservation is largely dependent on the rate of mineralization relative to the rate of plant tissue decay.

Fossil wood color and color distribution may indicate

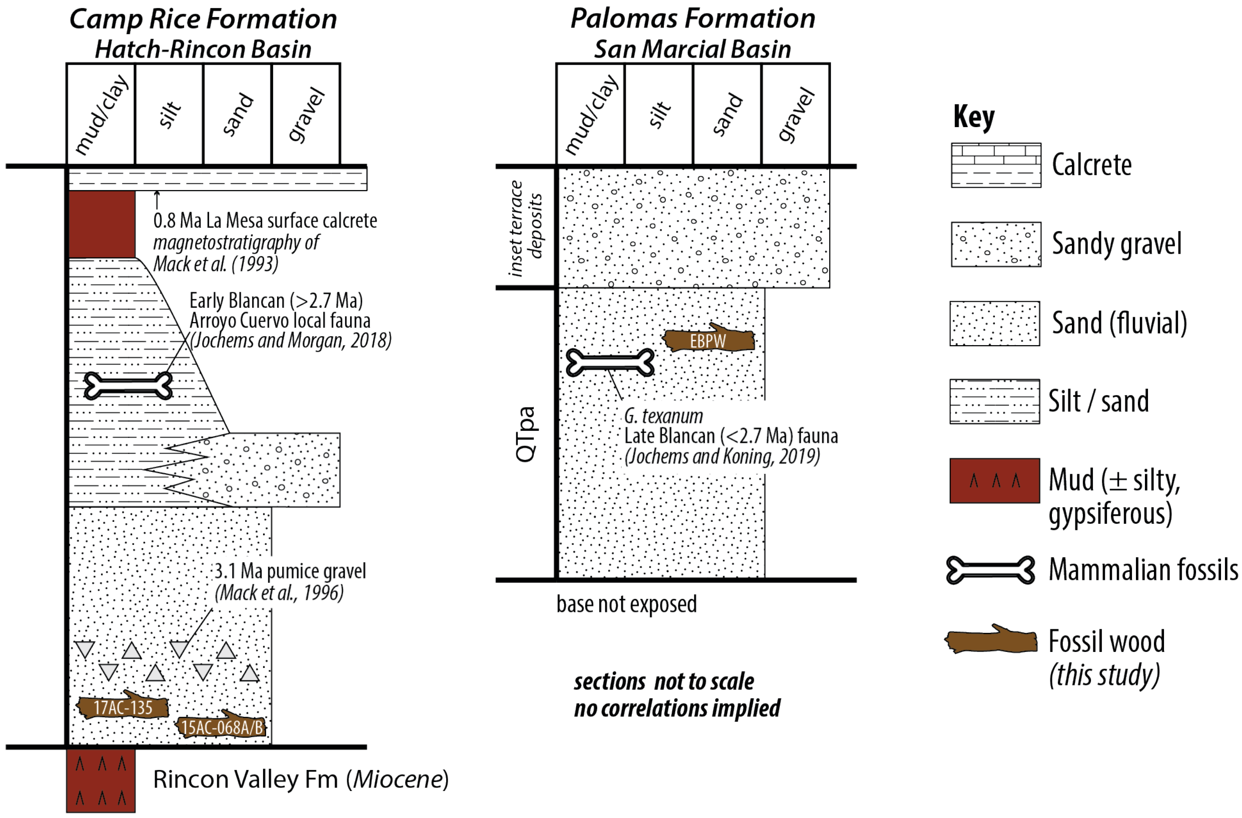

FIGURE 2. Schematic stratigraphic sections for fossil wood specimens from the Camp Rice and Palomas Formations. Samples were collected from axial-fluvial facies deposited by the ancestral Rio Grande. Lithologies are from Jochems (2017) and Koning and others (2020a). Fossil wood symbols are labeled with sample numbers given in Table 1.

changes in petrifaction conditions, mineralization processes, and/or geochemical setting (Mustoe and Acosta, 2016). Trace metals usually occur in very low concentrations in fossil wood samples that are opaque and black or white. However, color variations may arise as the result of episodic permineralization that occurs as hydrochemical conditions (pH, Eh, or temperature) fluctuate and silica minerals preferentially precipitate in different components of wood anatomy due to decreasing permeability (e.g., precipitation along tracheid walls followed by mineralization of larger diameter vessels in angiosperms). Geologic age and taxonomy do not appear to significantly influence fossil wood color (Mustoe and Acosta, 2016).

METHODS

Scanning electron microscopy (SEM) photomicrographs were made with a Tescan Vega SEM (Tesca, Brnu, Czech Republic) at Western Washington University (WWU). Each specimen was glued to a 1 cm diameter aluminum stub using epoxy resin. Electrical conductivity was provided by sputter-coating the specimens with Pd. Images were made at a beam energy of 15KeV. Petrographic thin sections were made at WWU, and thin-section photographs were made using a Zeiss polarizing microscope equipped with a 5-megapixel CMOS digital camera. Mineral identifications were made using XRD patterns obtained from a Panalytical X'Pert Pro diffractometer at the New Mexico Bureau of Geology and Mineral Resources. XRD samples were prepared as packed powders and analyzed using Ni-filtered Cu Kα radiation.

Fossil wood colors were described based on comparison of fresh-cut surfaces to Munsell soil color charts (Munsell Color, Grand Rapids, MI, USA).

RESULTS

Camp Rice Formation Samples

Table 1 lists mineralization species and estimated sample ages. Samples 15AC-068A and 15AC-068B were collected from float at the contact between axial-fluvial facies of the Pliocene-Pleistocene Camp Rice Formation and gypsiferous muds of the Miocene Rincon Valley Formation (Fig. 2). The samples are confidently assigned to the Camp Rice Formation because they feature coatings of quartzose sand deposited by the ancestral Rio Grande and numerous other fossil wood specimens were found in situ within the Camp Rice at similar stratigraphic intervals. At the 15AC-068 site, the Camp Rice is composed of light gray, non- to moderately carbonate-cemented, well-sorted, rounded, fine- to medium-grained sand (Jochems, 2017).

The outer surfaces of samples 15AC-068A and 15AC-068B exhibit well-preserved wood grain and minimal rounding (Fig. 3). The largest fragments observed are 35–40 cm in length and 15–20 cm in width. Fresh-cut inner surfaces exhibit dark gray colors (Table 1).

Calcified wood specimens effervesce strongly with 10%

TABLE 1. Summary information for fossil wood samples of the Camp Rice and Palomas formations.

Sample ID	Locality[1]	Unit[2]	Age	Munsell Color	Mineralization
15AC-068A	Arroyo Cuervo 5 km SW of Garfield, NM	Tcf	Pliocene	7.5-10YR 4/1 dark gray	Calcite >> quartz
15AC-068B	Arroyo Cuervo 5 km SW of Garfield, NM	Tcf	Pliocene	10YR to 2.5Y 4/1 dark gray	Calcite
17AC-135	Arroyo Cuervo 10 km NW of Hatch, NM	Tcf	Pliocene	10YR 7/3 very pale brown; 2.5Y 6/2 light brownish gray; N 8/ white; N 2.5/ black	Opal-CT ± chalcedony
Elephant Butte Petrified Wood (EBPW)	Paraje Well 17 km SW of Fort Craig, NM	QTpa	Early Pleistocene	10YR 8/1 to 6/1 white, light gray, and gray	Quartz >> calcite

[1] Precise locality information will be made available to qualified researchers.
[2] QTpa: Axial-fluvial facies of the Palomas Formation (Koning et al., 2020a); Tcf: Lower axial-fluvial facies of the Camp Rice Formation (Jochems, 2017).

HCl, and thin-section and SEM photomicrographs demonstrate that their internal anatomical structure is nearly obliterated (Fig. 4). XRD results indicate near-total replacement by calcite, although sample 15AC-068A contains ~6% quartz (Fig. 5).

Sample 17AC-135, opalized fossil wood, was collected in situ within axial-fluvial Camp Rice deposits approximately 10 m above the basal contact with the Rincon Valley Formation (Fig. 2). At this locality, the Camp Rice consists of yellowish brown to greenish, non-calcareous, poorly to moderately sorted, rounded, fine to coarse sand in lenticular, massive to planar cross-stratified beds with subordinate imbricated pebbles (Jochems, 2017). The age of ancestral Rio Grande sediments at this site is constrained by their stratigraphic location below a bed of pumice conglomerate dated at 3.1 Ma (Mack et al., 1996). Magnetostratigraphic data indicate that the underlying Camp Rice–Rincon Valley Formation contact is >3.6 Ma (Mack et al., 1993).

Opalized wood fragments from the Camp Rice Formation are generally <10 cm in length and width, and occur as subangular to subrounded fragments (Fig. 3) that were probably transported a short distance from their original location by the ancestral Rio Grande. Longitudinal surfaces exhibit strong wood grain defined by tracheids, and growth rings up to 2 mm wide may be observed on transverse sections.

Opalized wood specimens do not effervesce with 10% HCl. Thin-section and SEM photomicrographs show preserved anatomical structure (Fig. 6), but poor cellular detail prohibits taxonomic identification at the generic level. However, the presence of vessels (Fig. 6D) indicates that these samples are angiosperms and comparisons to modern hardwoods using the InsideWood database (North Carolina State University) suggest that they could belong to one of the following families (T. Dillhoff, pers. commun., 2017): Fabaceae (legume), Oleaceae (olive), or Sapindaceae (soapberry).

XRD results from a subsample of 17AC-135 contains 76% tridymite and 24% cristobalite (Fig. 5), indicating opal-CT mineralization, but chalcedony with semi-hemispherical (botryoidal) texture is observed filling vessels in thin sections of other subsamples that were not analyzed by XRD (Fig. 6F). Munsell colors correspond to these differences in mineralization: pure opal-CT fragments exhibit nearly pure white or

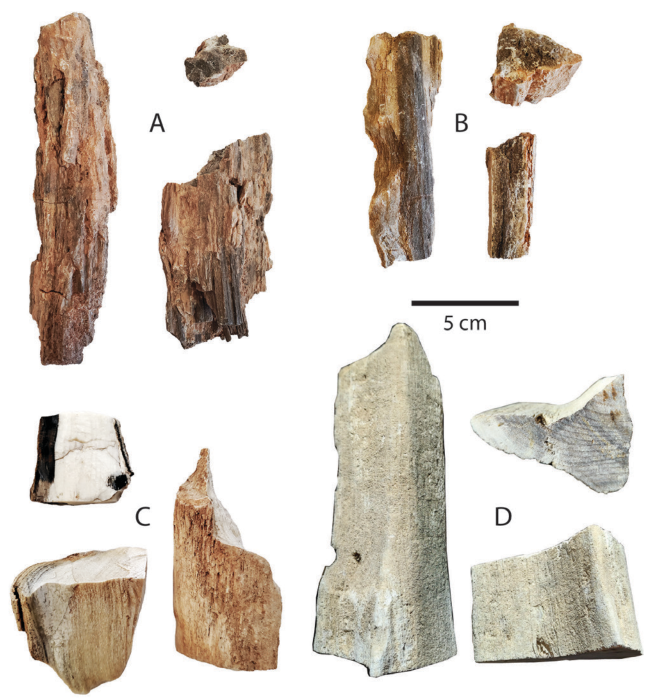

FIGURE 3. Hand samples of fossil wood collected from the upper Santa Fe Group. **A-B**) Calcified wood from the Arroyo Cuervo area near Hatch, New Mexico. Notice well-preserved wood grain on outer surfaces of longitudinal samples. Transverse sections exhibit gray color and obliterated internal anatomy. Samples 15AC-068A (A) and 15AC-068B (B). **C**) Opalized wood from the Arroyo Cuervo area. Black and white fragment is pure opal-CT whereas brownish fragments contain chalcedony. Growth rings may be observed on transverse surfaces. Sample 17AC-135. **D**) Silicified wood from the Paraje Well area. Smooth surfaces indicate transport in the ancestral Rio Grande stream system. Note well-preserved growth rings in a transverse section of sample Elephant Butte Petrified Wood (EBPW). Scale bar is for all samples.

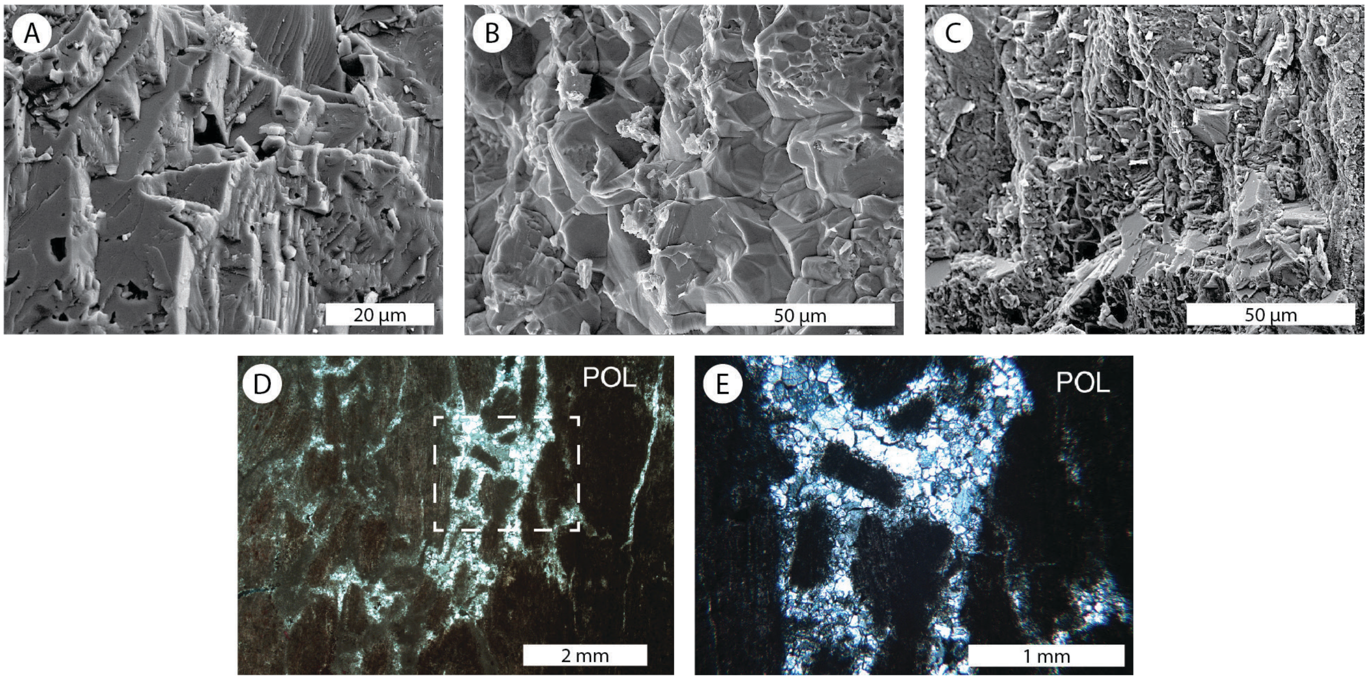

FIGURE 4. Scanning electron microscope (A-C) and thin-section (D-E) photomicrographs of calcified wood from the Camp Rice Formation. **A**) Polygonal calcite crystals in oblique transverse section obscures cell anatomy. Sample 15AC-068A. **B-C**) Calcite crystallization in longitudinal sections obscure cell anatomy but generally preserve vertical grain. Samples 15AC-068A (B) and 15AC-068B (C). **D-E**) Thin-section photomicrographs, polarized light, of longitudinal sections of sample 15AC-068B showing microcrystalline calcite precipitation replacing cellular architecture and filling fractures. Dashed box in (D) shows area of detail in (E).

black surfaces whereas fragments containing chalcedony have slightly brownish chromas (Table 1).

Palomas Formation Samples

Sample "Elephant Butte Petrified Wood" (hereafter "EBPW") was collected from float approximately 3–8 m below the upper contact of the axial-fluvial facies of the Palomas Formation. The samples are confidently assigned to the axial-fluvial facies of the Palomas Formation because of their landscape position. At the EBPW site, the Palomas Formation is composed of light brownish gray, loose to poorly consolidated, well-sorted, subrounded to subangular, fine- to coarse-grained sand with <25% pebbly sand beds (Koning et al., 2020a). The EBPW site is approximately 3 km southeast of and at or slightly above the same stratigraphic interval as ancestral Rio Grande sediments containing fossils of *Glyptotherium texanum* (D. Gillette and G. Morgan, pers. commun., in Jochems and Koning, 2019). The post-2.7 Ma arrival of this interchange species in North America constrains the EBPW site to early Pleistocene in age.

Fossil wood fragments from the Palomas Formation are generally 10–30 cm in length, 4–10 cm in width and occur as angular to subangular fragments (Fig. 3). Given the smoothness of samples' surfaces (similar to modern driftwood), they likely were transported a greater distance from their original location by the ancestral Rio Grande than were the Camp Rice Formation samples described above. Longitudinal surfaces exhibit strong wood grain defined by tracheids, and growth rings up to 4 mm wide may be observed on transverse sections.

Palomas Formation wood specimens do not effervesce with 10% HCl on fresh surfaces. Thin-section photomicrographs show preserved anatomical structure (Fig. 7), but poor cellular detail again prohibits taxonomic identification at the generic level. Like the Camp Rice Formation fossil wood specimens, Palomas Formation fossil woods exhibit vessels (Fig. 7) and are therefore angiosperms. XRD results from a subsample of EBPW contains 97% quartz and 3% calcite (Fig. 5).

DISCUSSION

Physical characteristics, mineralogy, and stratigraphic context allow several general inferences to be made with regards to fossil wood collected from Plio-Pleistocene basin-fill deposits in the southern Rio Grande rift. Together, these observations allow comparison of our results to wood petrifaction models proposed by previous workers.

Outer surfaces of all samples show well-preserved longitudinal wood grain. The lack of strongly rounded edges in Camp Rice Formation samples indicate that they were transported no more than a short distance along channels of the ancestral Rio Grande, whereas the rounded and abraded nature of Palomas Formation samples suggests a greater transport distance. In fact, Palomas Formation samples were initially mistaken for driftwood from the ca. 1990 highstand of Elephant Butte Reservoir. Petrifaction of Camp Rice Formation samples therefore occurred at or near the locations at which these specimens originated, but Palomas Formation samples might have been fossilized in an environment different from that in which they originated in growth. In either case, the timing of mineralization is not precisely constrained.

The geochemical conditions required for mineralization of

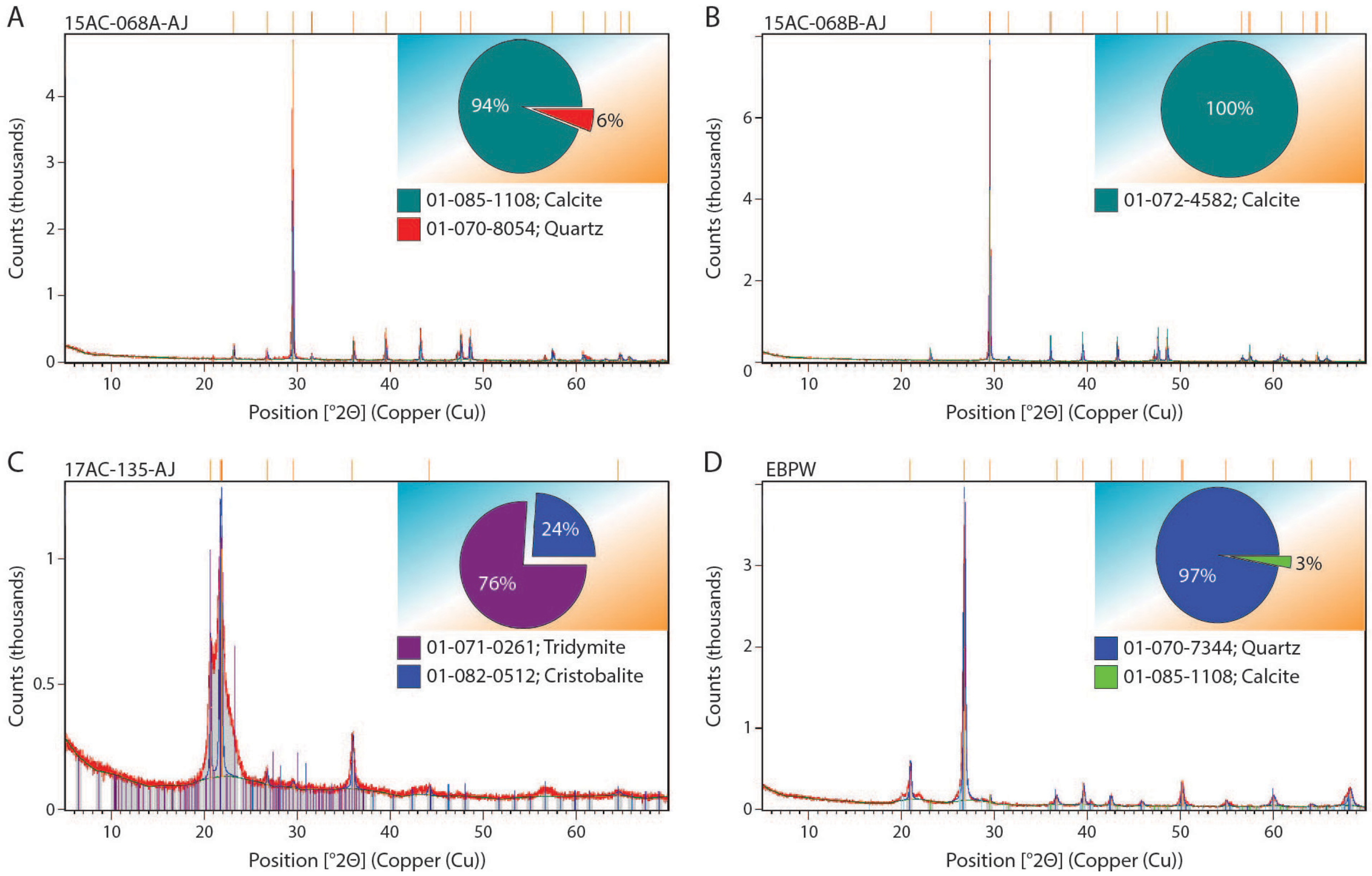

FIGURE 5. X-ray diffraction (XRD) patterns for all samples. **A-C**) Camp Rice Formation samples 15AC-068A (A), 15AC-068B (B), and 17AC-735 (C). **D**) Palomas Formation sample EBPW. Pie charts show interpreted proportions of mineral species present in each sample.

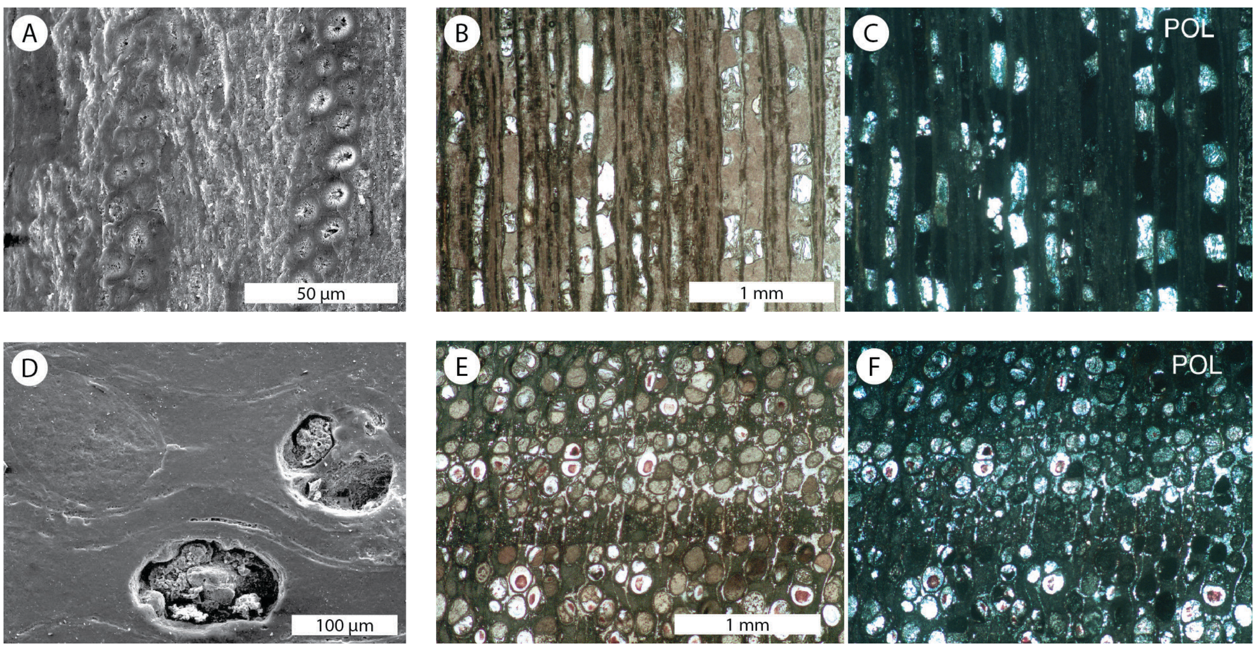

FIGURE 6. Scanning electron microscope (A, D) and thin-section (B-C, E-F) photomicrographs of opalized wood from the Camp Rice Formation (sample 17AC-135). **A**) SEM photomicrograph of tangential section showing tabular texture of opal-CT microcrystals filling vessels. **B-C**) Thin-section photomicrographs showing preservation of tracheid anatomy in tangential section. Plane light (B) and polarized light (C). **D**) SEM photomicrograph of transverse section showing vessels, characteristic of angiosperms. Vessels are filled with chalcedony exhibiting botryoidal texture; surrounding material is relatively featureless, vitreous opal-CT. **E-F**) Thin-section photomicrographs showing vessels and growth rings in transverse section. Birefringent chalcedony fills many vessels. Plane light (E) and polarized light (F).

the samples described in this study were highly localized and probably ephemeral. Fossil wood samples collected from similar stratigraphic intervals of the Camp Rice Formation exhibit both calcite and silica mineralization, and we suggest that this is due to hydrogeochemical conditions that operated in discrete spatiotemporal settings. Calcite occurs frequently as cement and as matrix in paleosols or spring deposits in Plio-Pleistocene basin-fill of the Rio Grande rift (e.g., Mozley et al., 1995; Mack et al., 2000). However, its prevalence in Camp Rice sample 15AC-068 may be best explained by the concretion model of Mozley and Davis (2005), in which calcite precipitation is localized along groundwater flow paths down-gradient from decaying organic matter.

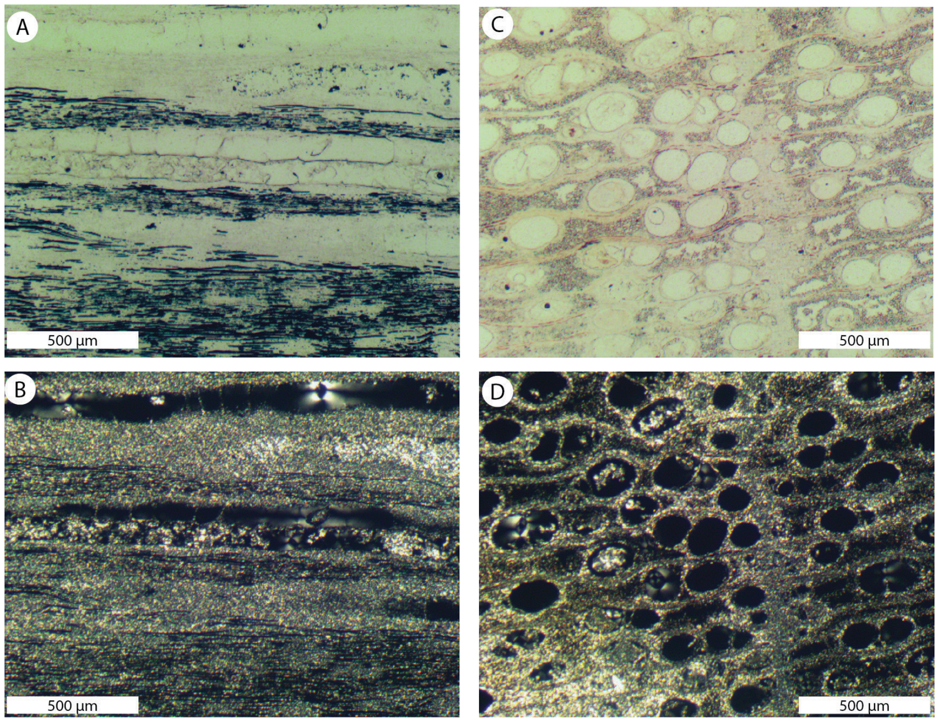

FIGURE 7. Thin-section photomicrographs of fossilized wood from the Palomas Formation (sample EBPW). **A**) Plane light and **B**) cross-polarized light photomicrographs showing tracheid anatomy in tangential section. **C**) Plane light and **D**) cross-polarized light photomicrographs showing vessels and growth rings in transverse section.

Alternatively, porewater chemistry in the saturated zone may have favored calcification due to carbonate-mineral reactions over a broader area as indicated by relatively common carbonate cements in the axial-fluvial Camp Rice facies (Jochems, 2017; Jochems and Morgan, 2018). In any case, calcification of fossil wood probably occurred under alkaline conditions long after the decomposition of original organic matter in the wood (cf. Mustoe, 2018), as indicated by the poorly preserved cellular detail of the samples. The timing of calcite mineralization of wood is constrained only by a minimum age of ~0.8 Ma for the Camp Rice Formation (Mack et al., 1993), after which vertical incision of the ancestral Rio Grande was accompanied by a falling water table.

Silicification of wood requires geochemical conditions that are known, but relatively uncommon, in the Rio Grande rift. Diagenesis cannot be invoked as a control on silicification because the Camp Rice Formation has not experienced burial depths of >100 m (Mack et al., 1994), and stratigraphic relations indicate that the Palomas Formation in the San Marcial Basin likewise experienced shallow burial since its deposition. However, geothermal waters are locally found throughout the rift, often in association with Neogene-Quaternary fault systems (Witcher, 1988; Pepin et al., 2022). Some fault systems are associated with magma bodies at depth, but others are amagmatic and hydrothermal conditions are instead driven by upwelling of deep waters along steepened geothermal gradients (e.g., Person et al., 2013). Rapid, adiabatic upwelling along non-mineralized fault systems results in precipitation of silica species at and near the surface (Fournier et al., 1974). We speculate that opalized wood of the Camp Rice Formation formed under such conditions along the nearby Arroyo Cuervo fault, perhaps aided by the proximity of the contact between the Camp Rice Formation and the underlying Rincon Valley Formation, a clay-rich unit that acts as an aquiclude (Jochems, 2017).

An alternative or perhaps coeval source for silica in the Camp Rice Formation samples is upwelling of silica-laden waters along the Sierra de las Uvas fault system to the south. The Sierra de las Uvas is a mountain range cored by volcanic rocks, including pyroclastic rocks that may have been the source of dissolved silica. Perhaps meteoric water infiltrated these strata, was heated at depth, and then rapidly upwelled along the Sierra de las Uvas fault before being transported in groundwater flow toward discharge points at or near the ancestral Rio Grande in the vicinity of sample 17AC-135. Based on local well data, King and others (1969) inferred that groundwater flow could be focused along paleochannels in the Camp Rice Formation.

The source of silica-bearing fluids in the Palomas Formation is unknown. Unlike Camp Rice Formation fossil wood sites, the Palomas Formation fossil wood site is not in close proximity to known fault systems. Travertine is observed along the western boundary fault of the Little San Pascual Mountains approximately 30 km to the northeast. However, these strata appear to be of limited spatial extent and are inferred to be middle or late Pleistocene in age (Koning et al., 2020b). There is no observed silica cement in the deposits hosting the fossil wood samples or in superjacent strata. The high porosity and permeability of the Palomas Formation's wood-bearing sediments could have facilitated high rates of groundwater—and therefore dissolved silica—flux through buried wood. However, statements concerning silica source in these waters are speculative. Biogenic silica is an important silica source in the origin of silicified sediments (Hesse, 1989), but its potential role in Palomas Formation fossil wood silicification is unknown.

Several observations may be made regarding the relative timing of silicification and mineralization pathways in Camp Rice and Palomas formation samples. First, opalized wood of the Camp Rice Formation underwent at least two phases of mineralization, likely with opal-CT as a primary mineral. It is not known whether opal-A ever precipitated in these specimens, but the lack of characteristic lepispheres in SEM imagery suggests that it did not. Partial filling of vessels with chalcedony during a later episode(s) of mineralization suggests that certain conductive parts of the wood anatomy retained permeability after opal-CT formed on cell walls. The initial mineralization on cell walls observed in the samples fits the model of Leo and Barghoorn (1976), but secondary filling of open vessels by chalcedony indicates a more complex paragenesis consistent with the multi-hydrothermal episode model of Mustoe (2015) and studies of Pliocene wood silicification from Idaho (Viney et al., 2016).

Second, the morphological and mineralogical uniqueness of the Palomas Formation fossil wood samples as compared to Camp Rice Formation samples suggests a different genetic process for fossilization. Vessels remain open in the Palomas Formation fossil woods, which has been interpreted as an indication that fossilization began with amorphous silica precipitation within cells (Mustoe and Dillhoff, 2022). The lack of secondary vessel filling in Palomas Formation samples perhaps suggests a single stage of mineralization in contrast to the possible multi-stage fossilization of Camp Rice Formation samples.

Third, the paradigm of quartz crystallization associated with older petrified wood specimens (e.g., Paleogene to Cretaceous) does not hold true for the Camp Rice and Palomas samples discussed in this study. Previous workers have suggested that disordered opal-CT transforms to microgranular chalcedony or euhedral quartz crystals over very long timespans (Stein, 1982). However, quartz mineralization is documented in fossil wood of middle to late Pleistocene age at Ban Tak Fossil Forest in Thailand (Philippe et al., 2013) and in late Pleistocene siliceous sediments in the East African Rift (Behr, 2002), suggesting that long time intervals are not requisite for quartz mineralization. Clearly, long intervals of geologic time are not required for this transformation because quartz crystallization was observed only in the Pleistocene samples of the San Marcial Basin, and chalcedony occurs as a distinct mineral phase in the Camp Rice samples.

CONCLUSIONS

Fossil wood samples from axial-fluvial (ancestral Rio Grande) facies of the Plio-Pleistocene Camp Rice and Palomas formations include calcified and silicified specimens, the latter identified as angiosperms based on preserved anatomical features. The Camp Rice Formation samples were likely mineralized near their original location and their gross mineralogy ranges from nearly 100% calcite to dominantly opal-CT with chalcedony filling vessels in some specimens. The Palomas Formation samples were transported some distance down the ancestral Rio Grande channel system before being deposited and silicified. XRD analyses indicate that they primarily contain crystalline quartz with a minor amount of calcite. Diagenesis is dismissed as a driver of silicification because the source basin-fill deposits have not undergone extensive burial. Ideal hydrothermal conditions for opalization of Camp Rice Formation deposits may have been facilitated by their proximity to relatively young (Plio-Pleistocene) fault systems and silica-rich volcanic rocks and stratigraphic occurrence above an extensive aquitard (Rincon Valley Formation), but more data is needed to confirm this hypothesis. Perhaps similar conditions led to silicification of fossil wood deposits in the Palomas Formation, but currently no evidence is known for viable fossil hot spring systems in the San Marcial Basin.

Although the geochemical conditions and timing of mineralization cannot be precisely constrained, the silica species present and ages of the source deposits provide important clues to silicification pathways and genesis. Notably, the Camp Rice and Palomas formation samples demonstrate that silica species in fossil wood are not a reliable proxy for geologic age because crystalline quartz is present in the youngest samples studied (early Pleistocene). Furthermore, observations of opalized wood from the Camp Rice Formation support the longstanding paradigm of initial silicification on cell walls, yet challenge other models of single-stage mineralization beginning with amorphous silica. Wood petrifaction is a complex process, and future research should seek to address silica sources where wood silicification does not have a clear geothermal provenance as in the Camp Rice and Palomas formations.

ACKNOWLEDGMENTS

We thank Mike Timmons and Nelia Dunbar for their support of the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) STATEMAP program, under which this research was initiated. Kelsey McNamara and Virgil Lueth (NMBGMR) handled XRD analyses and discussion about mineralization characteristics in the samples. Tad Dillhoff (Evolving Earth Foundation) kindly provided identifications of potential family taxonomy for the Camp Rice Formation samples. We gratefully acknowledge reviews from Scott Elrick, Howard Falcon-Lang, and guidebook editor W. John Nelson.

REFERENCES

Augustithis, S.S., 1982, Atlas of sphaeroidal textures and their genetic significance: Athens, Theophrastus Publications, p. 71–73, 241–250.

Ballhaus, C., Gee, C.T., Bockrath, C., Greef, K., Mansfeldt, T., and Rhede, D., 2012, The silicification of trees in volcanic ash—An experimental study: Geochimica et Cosmochimica Acta, v. 84, p. 62–74, doi:10.1016/j.gca.2012.01.018.

Behr, H.J., 2002, Magadiite and Magadi chert: A critical analysis of the silica sediments in the Lake Magadi Basin, Kenya, *in* Renaut, R.W., and Ashley, G., eds., East African Sedimentation: SEPM Special Publication, v. 73, p. 233–246.

Brues, C.T., 1936, Evidences of insect activity preserved in fossil wood: Journal of Paleontology, v. 10, p. 637–643.

Buurman, P., 1972, Mineralization of fossil wood: Scripta Geologica, v. 12, p. 1–43.

Elrick, S.D., Nelson, W.J., and Lucas, S.G., 2017, Fossil wood from late Pennsylvanian sabkhas in Socorro County, New Mexico, *in* Lucas, S.G., DiMichele, W.A., and Krainer, K., eds., Carboniferous-Permian Transition in Socorro County, New Mexico: New Mexico Museum of Natural History and Science Bulletin 77, p. 101–108.

Estrada-Ruiz, E., Upchurch, G.R., Wheeler, E.A., and Mack, G.H., 2012, Late Cretaceous angiosperm woods from the Crevasse Canyon and McRae formations, south-central New Mexico, USA: Part 1: International Journal of Plant Sciences, v. 173, p. 412–428, doi:10.1086/664714.

Estrada-Ruiz, E., Wheeler, E.A., Upchurch, G.R., and Mack, G.H., 2018, Late Cretaceous angiosperm woods from the McRae Formation, south-central New Mexico, USA: Part 2: International Journal of Plant Sciences, v. 179, p. 136–150, doi:10.1086/695503.

Falcon-Lang, H.J., Kurzawe, F., and Lucas, S.G., 2016, A Late Pennsylvanian coniferopsid forest in growth position, near Socorro, New Mexico, U.S.A.: Tree systematics and palaeoclimatic significance: Review of Palaeobotany and Palynology, v. 225, p. 67–83, doi:10.1016/j.revpalbo.2015.11.008.

Felix, J., 1897, Unterschungen über den versteinerungsprozess un erhaltungszustand planslicher membranen: Zeithschrift der Deutsche Geologische Gessellschaft, v. 49, p. 182–192.

Fournier, R.O., White, D.E., and Truesdell, A.H., 1974, Geochemical indicators of sub-surface temperature: Part I. Basic assumptions: Journal of Research of the U.S. Geological Survey, v. 2, p. 259–262.

Hawley, J.W., and Kottlowski, F.E., 1969, Quaternary geology of the south-central New Mexico border region, *in* Kottlowski, F.E., and LeMone, D.V., eds., Border Stratigraphy Symposium: New Mexico Bureau of Mines and Mineral Resources Circular 104, p. 89–115.

Herdianita, N.R., Browne, P.R.L., Rodgers, K.A., and Campbell, K.A., 2000, Mineralogical and textural changes accompanying ageing of silica sinter: Mineralium Deposita, v. 35, p. 48–62, doi:10.1007/s001260050005.

Hesse, R., 1989, Silica diagenesis: Origin of inorganic and replacement cherts: Earth-Science Reviews, v. 26, no. 1–3, p. 253–284, doi: 10.1016/0012-8252(89)90024-X.

Hudson, P., and Boucher, L.D., 2006, Using wood anatomy to estimate Late Cretaceous paleoclimate in New Mexico (abs.): Geological Society America Abstracts with Programs, v. 38, no. 7, p. 491.

Jefferson, T.H., and McDonald, D.I., 1981, Fossil wood from South Georgia: British Antarctic Survey Bulletin, v. 54, p. 57–64.

Jochems, A.P., 2015, Geologic map of the Williamsburg NW 7.5-minute quadrangle, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map OF-GM 251, scale 1:24,000.

Jochems, A.P., 2017, Geologic map of the Arroyo Cuervo 7.5-minute quadrangle, Doña Ana and Sierra Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map 261, scale 1:24,000.

Jochems, A.P., and Koning, D.J., 2019, Geologic map of the Black Hill 7.5-minute quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map 274, scale 1:24,000.

Jochems, A.P., and Morgan, G.S., 2018, A stable isotope record from paleosols and groundwater carbonate of the Plio-Pleistocene Camp Rice Formation, Hatch-Rincon Basin, southern New Mexico: New Mexico Geological Society, Guidebook 69, p. 109–117.

Kastner, M., Keene, J.B., and Gieskes, J.M., 1977, Diagenesis of siliceous oozes—I. Chemical controls on the rate of opal-A to opal-CT transformation—An experimental study: Geochimica et Cosmochimica Acta, v. 41, p. 1041–1059, doi:10.1016/0016-7037(77)90099-0.

King, W.E., Hawley, J.W., Taylor, A.M., and Wilson, R.P., 1969, Hydrogeology of the Rio Grande valley and adjacent intermontane areas of southern New Mexico: New Mexico Water Resources Research Institute, New Mexico State University, Report 6, 65 p., 1 plate.

Koning, D.J., Jochems, A.P., Hobbs, K.M., Pearthree, K.S., and Love, D.W., 2020a, Geologic map of the Paraje Well 7.5-minute quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map 286, scale 1:24,000.

Koning, D.J., Pearthree, K.S., Jochems, A.P., and Love, D.W., 2020b, Geologic map of the San Marcial 7.5-minute quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map 287, scale 1:24,000.

Kues, B.S., and Lucas, S.G., 1979, Summary of the paleontology of the Santa Fe Group (Mio-Pliocene), north-central New Mexico: New Mexico Geological Society, Guidebook 30, p. 237–241.

Leeder, M.R., Mack, G.H., and Salyards, S.L., 1996, Axial–transverse fluvial interactions in half-graben: Plio-Pleistocene Palomas Basin, southern Rio Grande rift, New Mexico, USA: Basin Research, v. 12, p. 225–241.

Leo, R.F., and Barghoorn, E.S., 1976, Silicification of wood: Botanical Museum leaflets, Harvard University, v. 25, p. 1–47, doi:10.5962/p.295209.

Lozinsky, R.P, 1986, Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 187, 40 p.

Lozinsky, R.P. and Hawley, J.W., 1986, The Palomas Formation of south-central New Mexico—A formal definition: New Mexico Geology, v. 8, no. 4, p. 73–82.

Mack, G.H., Salyards, S.L., and James, W.C., 1993, Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas formations in the Rio Grande rift of southern New Mexico: American Journal of Science, v. 293, p. 49–77.

Mack, G.H., Cole, D.R., James, W.C., Giordano, T.H., and Salyards, S.L., 1994, Stable oxygen and carbon isotopes of pedogenic carbonate as indicators of Plio-Pleistocene paleoclimate in the southern Rio Grande rift, south-central New Mexico: American Journal of Science, v. 294, p. 621–640.

Mack, G.H., McIntosh, W.C., Leeder, M.R., and Curtis Monger, H., 1996, Plio-Pleistocene pumice floods in the ancestral Rio Grande, southern Rio Grande rift, USA: Sedimentary Geology, v. 103, p. 1–8.

Mack, G.H., Cole, D.R., and Treviño, L., 2000, The distribution and discrimination of shallow, authigenic carbonate in the Pliocene–Pleistocene Palomas Basin, southern Rio Grande rift: Geological Society of America Bulletin, v. 112, p. 643–656.

Matysová, P., Rössler, R., Götze, J., Leichmann, J., Forbes, G., Taylor, E.L., Sakala, J., and Grygar, T., 2010, Alluvial and volcanic pathways to silicified plant stems (Upper Carboniferous–Triassic) and their taphonomic and palaeoenvironmental meaning: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 292, p. 127–143, doi:10.1016/j.palaeo.2010.03.036.

McBride, E.F., Picard, M.D., and Milliken, K.L., 2003, Calcite-cemented concretions in Cretaceous sandstone, Wyoming and Utah, USA: Journal of Sedimentary Research, v. 73, p. 462–483, doi:10.1306/111602730462.

Mizutani, S., 1970, Silica minerals in the early stages of diagenesis: Sedimentology, v. 15, p. 419–436.

Mizutani, S., 1977, Progressive ordering of cristobalitic silica in the early stage of diagenesis: Contributions to Mineralogy and Petrology, v. 61, p. 129–140.

Morgan, G.S. and Lucas, S.G., 2012, Cenozoic vertebrates from Sierra County, southwestern New Mexico: New Mexico Geological Society, Guidebook 63, p. 525–540.

Mozley, P.S., and Davis, J.M., 2005, Internal structure and mode of growth of elongate calcite concretions: Evidence for small-scale, microbially induced, chemical heterogeneity in groundwater: Geological Society of America Bulletin, v. 117, p. 1400–1412, doi:10.1130/B25618.1.

Mozley, P., Beckner, J., and Whitworth, T.M., 1995, Spatial distribution of calcite cement in the Santa Fe Group, Albuquerque Basin, NM: Implications for ground-water resources: New Mexico Geology, v. 17, no. 4, p. 88–93.

Mustoe, G.E., 2008, Mineralogy and geochemistry of late Eocene silicified wood from Florissant Fossil Beds National Monument, Colorado, *in* Meyer, H.W., and Smith, D.M., eds., Paleontology of the Upper Eocene Florissant Formation, Colorado: Geological Society of America Special Paper 435, doi:10.1130/2008.2435(09).

Mustoe, G., 2015, Late Tertiary petrified wood from Nevada, USA: Evidence of multiple silicification pathways: Geosciences, v. 5, p. 286–309, doi:10.3390/geosciences5040286.

Mustoe, G., 2017, Wood petrifaction: A new view of permineralization and replacement: Geosciences, v. 7, 119, doi:10.3390/geosciences7040119.

Mustoe, G., 2018, Mineralogy of non-silicified fossil wood: Geosciences, v. 8, 85, doi:10.3390/geosciences8030085.

Mustoe, G., and Acosta, M., 2016, Origin of petrified wood color: Geosciences, v. 6, 25, doi:10.3390/geosciences6020025.
Mustoe, G.E., and Beard, G., 2021, Calcite-mineralized fossil wood from Vancouver Island, British Columbia, Canada: Geosciences, v. 11, 38, doi:10.3390/geosciences11020038.
Mustoe, G.E., and Dillhoff, T.A., 2022, Mineralogy of Miocene Petrified Wood from Central Washington State, USA: Minerals, v. 12, 131, doi: 10.3390/min12020131.
Northrop, S.A., 1962, New Mexico's fossil record: New Mexico Quarterly, v. 32, no. 1, 77 p.
Pepin, J.D., Robertson, A.J., and Kelley, S.A., 2022, Salinity contributions from geothermal waters to the Rio Grande and shallow aquifer system in the transboundary Mesilla (United States)/Conejos-Médanos (Mexico) Basin: Water, v. 14, doi:10.3390/w14010033.
Person, M., Phillips, F., Kelley, S., Timmons, S., Pepin, J., Blom, L., Haar, K., and Murray, M., 2013, Assessment of the sustainability of geothermal development within the Truth or Consequences hot-springs district, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Report 551, 49 p.
Phillippe, M., Boonchai, N., Ferguson, D.K., Jia, H., and Songtham, W., 2013, Giant trees from the middle Pleistocene of northern Thailand: Quaternary Science Reviews, v. 65, p. 1–4.
Scurfield, G., and Segnit, E.R., 1984, Petrifaction of wood by silica minerals: Sedimentary Geology, v. 39, p. 149–167.
Seager, W.R., Clemons, R.E., Hawley, J.W., and Kelley, R.E., 1982, Geology of northwest part of Las Cruces 1° x 2° sheet, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 53, scale 1:125,000.
Sion, B.D., Phillips, F.M., Axen, G.J., Harrison, J.B.J., Love, D.W., and Zimmerer, M.J., 2020, Chronology of terraces in the Rio Grande rift, Socorro basin, New Mexico: Implications for terrace formation. Geosphere, v. 16, no. 6, p.1457–1478, doi: 10.1130/GES02220.1.
St. John, R.N., 1927, Replacement vs. impregnation in petrified wood: Economic Geology, v. 22, p. 729–739.
Stein, C.L., 1982, Silica recrystallization in petrified wood: Journal of Sedimentary Research, v. 52, p. 1277–1281.
Sweeney, I.J., Chin, K., Hower, J.C., Budd, D.A., and Wolfe, D.G., 2009, Fossil wood from the middle Cretaceous Moreno Hill Formation: Unique expressions of wood mineralization and implications for the processes of wood preservation: International Journal of Coal Geology, v. 79, p. 1–17, doi:10.1016/j.coal.2009.04.001.
Viney, M., Dietrich, D., Mustoe, G., Link, P., Lampke, T., Götze, J., and Rößler, R., 2016, Multi-stage silicification of Pliocene wood: Re-examination of an 1895 discovery from Idaho, USA: Geosciences, v. 6, p. 21, doi:10.3390/geosciences6020021.
Von, I.D.V., and Correns, C.W., 1950, Zur geochemie der diagenese: Geochimica et Cosmochimica Acta, v. 1, p. 49–54.
Wheeler, E.A., McClammer, J., and LaPasha, C.A., 1995, Similarities and differences in dicotyledonous woods of the Cretaceous and Paleocene. San Juan Basin, New Mexico, USA: IAWA Journal, v. 16, p. 223–254, doi:10.1163/22941932-90001407.
Williams, L.A., and Crerar, D.A., 1985, Silica diagenesis; II, General mechanisms: Journal of Sedimentary Petrology, v. 55, p. 312–321.
Williams, L.A., Parks, G.A., and Crerar, D.A., 1985, Silica diagenesis; I, Solubility controls: Journal of Sedimentary Petrology, v. 55, p. 301–311.
Witcher, J.C., 1988, Geothermal resources of southwestern New Mexico and southeastern Arizona: New Mexico Geological Society, Guidebook 39, p. 191–197.