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A New Look at Cenozoic Fossil Wood from Thailand

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Abstract: Thailand contains two notable fossil forest regions. Pleistocene fluvial sediments in the Tak region in the northern highlands contain silicified trunks of large trees. Deposits in the Khorat Plateau in northeast Thailand contain a multitude of wood fossils that span a probable age range of Miocene to Pleistocene. At Ban Tak fossil logs are primarily mineralized with crystalline quartz. Incomplete mineralization is characteristic of the Tak wood, with intercellular spaces commonly remaining open. The resulting permeability allows penetration of moisture, and allows introduction of microbes and the accumulation of clays, iron oxides, soluble salts and other materials that may cause discoloration and deterioration. Hydration swelling of these components results in stress. Excavation of the huge logs means that they occupy topographically low positions prone to flooding during the monsoon season. These factors make the fossils vulnerable to weathering. A variety of methods have been employed in attempts to reduce the damage, including the construction of various styles of shelters to protect the fossil logs from direct precipitation. At Khorat, compositions of individual specimens range from pure quartz and pure opal to mixtures of the two polymorphs. Many specimens are preserved indoors in the Khorat Fossil Museum in Mueang Nakhon Ratchasima District, both as indoor exhibits and as outdoor displays in a garden plaza. The environmental complexities at the Tak and Khorat fossil wood localities challenge conservators, but their creative attempts provide useful lessons for future preservation efforts. Our report describes the geologic setting and our research mineralogy of specimens at both localities, and discusses conservation strategies.

Keywords: Tak; Khorat; Southeast Asia; paleobotany; petrified wood; conservation; weathering

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1. Introduction

Paleozoic and Mesozoic formations in Thailand include plant remains, but the record of ancient forests is best known from Cenozoic deposits. These strata include two spectacular occurrences. During the Pleistocene and Holocene, extensive sediments were deposited along Thailand's four main river systems: Ping, Wang, Yom, and Nan. Down-cutting of the river systems as a result of regional uplift produced multi-leveled terraces [1]. Abundant fossil logs have been discovered in two principal regions, Tak in the northern highlands, and the Khorat Plateau in northeast Thailand (Figure 1). Silicified logs preserved in Pleistocene gravels at Ban Tak include the world's longest known angiosperm trunk. Quaternary fluvial sediments of the Khorat Plateau have yielded a multitude of fossil wood specimens.

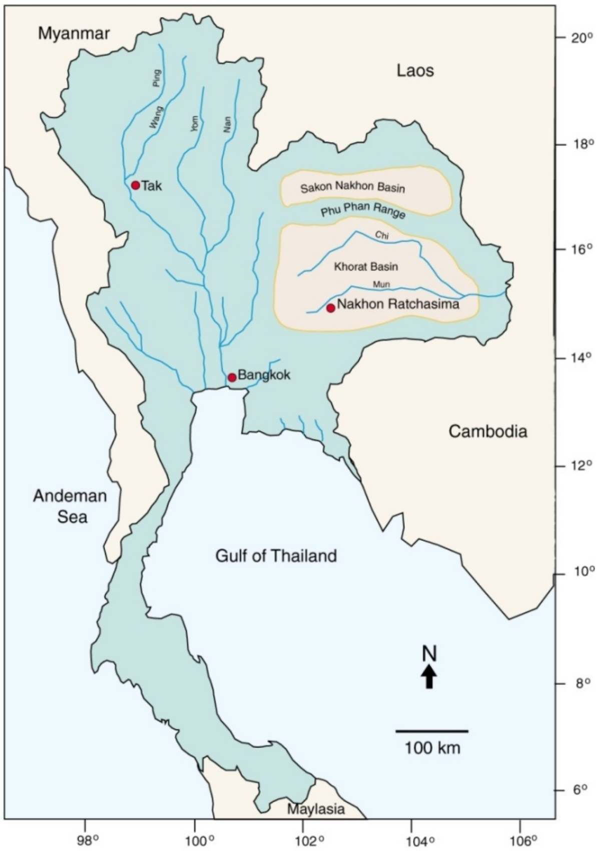

Figure 1. Thailand Map showing the main rivers in the north and northeast. Important petrified wood sites are in Tak Province and the Khorat Basin.

For decades, scientists, educational institutes, government agencies, and local communities have strived to protect these sites, using shelters to protect fossil logs from weathering in the highly-seasonal tropical climate. Possible use of chemical consolidants and water repellents has been a much-debated issue. Meanwhile, fossil wood in outdoor settings continues to deteriorate. We report the results of our study of the mineralogy and microscopy of fossil trees from the Tak and Khorat localities, review earlier studies, and discuss various conservation strategies.

Our focus is on scientific aspects, but Thailand fossil forests have international importance for a variety of reasons. Petrified wood sites in Tak and Khorat generate significant income for local revenue via geotourism. The establishment of the petrified wood museum and national park brought each site more than 100,000 visitors annually before the 2019 arrival of the Covid pandemic. The sites are potentially important for geo-education programs, as well as providing a model for conservation strategies for other fossil sites. For these reasons, solving the problem of weathering to ensure long term stability is a high priority.

Conservation planning has been a collaboration of local, national and international efforts. In 2015, representatives of UNESCO Global Geoparks (UGGp) Council, Nickolas Zouros, a founder of the Natural History Museum of Lesvos Petrified Forest and Lesvos Island UGGp, and Zhang Jianping, a vice-chairperson of the UGGp, and Patrick McKeever, UNESCO Earth Science and Risk Reduction, visited Thailand and made on-site recommendations of potential for geopark development, including Tak and Khorat. Meetings also included governors and other policymakers at related organizations, including the DMR. Khorat Geopark submitted the UNESCO Global Geopark application dossier in 2019 with siteevaluation in 2022.

2. Materials and Methods

Ten specimens from seven fossil logs on in situ display at the Petrified Forest site in Doi Soi Malai—Mai Klai Pen Hin National Park (Ban Tak) were sampledby N. Boonchai and C. Aranyanark. Eleven specimens of wood from the Khorat Plateau were provided by P. Jintasakul. These samples were used for the mineralogic study of unweathered fossil wood. Scanning electron microscope images were made at Western Washington University using a Tescan Vega III SEM (Tescan, Brno, Czech Republic) equipped with an Oxford EDS detector using Aztec software (Oxford Instruments, Abingdon, UK). X-ray diffraction (XRD) patterns came from a Rigaku Miniflex II diffractometer (Rigaku, Tokyo, Japan) at the W.W.U. Advanced Materials Science and Engineering Center. Optical Microscope photos were made using a Zeiss petrographic microscope (Carl Zeiss Microscopy, White Plains, NY, USA) and a Bausch and Lomb Stereoscan microscope (https:/microscopecentral.com (accessed on 20 July 2022), using a 5 megapixel CMOS digital microscope camera. Density measurements were determined with a Metler analytical balance (Mettler–Toledo LLC, Columbus, OH, USA) equipped with a specific gravity accessory, as described by Mustoe [2].

Studies of Ban Tak fossil wood were conducted in Thailand from 2004 to 2021. Field teams investigated petrified trunks and their surroundings at macroscopic and microscopic levels. Digital data loggers and weather station were used to monitor fluctuations in temperature and relative humidity (RH). Samples from the seven trunks were studied for taxonomy and conservation purposes. Specimens from each site were cut into $3 \times 3 \times 6$ cm blocks for laboratory testing of physical properties in 2017. Samples from BT-4, BT-5, and BT-7 were sent to Krit Won-in at Kasetsart University in Bangkok, Thailand for thermoluminescence (TL) dating. Physical testing of conservation samples was tested by C. Aranyanark using laboratory facilities at the Scientific and Technological Research Equipment Centre (STREC) at Chulalongkorn University, also in Bangkok. Laboratory investigations of weathered samples included X-ray diffraction (Bruker AXS D-8 Discover model, Bruker Corporation, Billerica, MA, USA; www.bruker.com (accessed on 20 July 2022), X-ray fluorescence (Bruker S8 Tiger model), SEM/EDS analysis (JEOL JSM-6610 LV SEM, JEOL Ltd., Tokyo, Japan) with an energy-dispersive X-ray spectrometer (Oxford X-Max 50UK, Oxford Instruments, Abingdon, Oxfordshire, UK). Petrographic thin sections were used to examine altered surfaces, fossil wood textures, and cementing materials. Also tested were compressive strength, flexural strength, porosity and pore diameters, density, water absorption, pH, electrical conductivity, salinity, and determination of acids and salts.

Materials used for experimental conservation treatments included consolidants, water repellents and restoration fillers. Depending on specimen size, chemicals were applied by brushing, spraying, or injection. Prior to treatment, specimen surfaces were gently cleaned using water or steam. Fragile samples that were sprayed with chemicals without prior surface cleaning. After treatment, specimens were protected from sunlight for 2–3 days because heat can cause the chemicals to evaporate before they penetrate deeply into the specimen. Subsequent evaluations were based on penetration depth, porosity and water absorption.

Field visits to Ban Tak in 2021 included observations of texture, color variations related to mineralogy, macroporosity, visible evidence of weathering and deterioration, fragility, scaling, exfoliation, fissures, fracturing, cracking and determination of soil pH.

3. Ban Tak Fossil Forest

Large silicified tree trunks are preserved in gravel deposits along the channel of the Ping and Wang Rivers in the early Pleistocene [3]. The first petrified trunk was partially exposed about a meter long, discovered by a villager in October 2003 in a tropical dry dipterocarp forest region in Tak-Ok Subdistrict, Ban Tak District. The area was protected under Thailand's National Reserved Forest Act. The discovery was reported to related authorities, which led to an excavation that revealed the length of the partially exposed log was more than 20 m, with a width of 1.83m at that height. The lower trunk terminated in a buttress that had a width of 4.38 m measured ~2 m from the base. These dimensions are characteristic of a canopy tree.

The area then proposed as a protected area, namely Khao Phra Baht Forest Park, later changed into "Petrified Forest Park" after the locals found six other petrified trunks (Figure 2). The lengths of buried trunks were determined using ground penetrating radar (GPR).Management of the area involves three leading agencies: (1) Forest Research Management Office No. 4 (Tak) of the Royal Forest Department (RFD) for the land, (2) the Conservation Area Administration Office 14 (Tak) of the Department of National Park, Wildlife, and Plant Conservation (DNP) for park administration, and (3) Bureau of Mineral Resources Office Region 1 (Lampang) of the Department of Mineral Resources (DMP) for the petrified trunks at each site. The three departments are under Thailand's Ministry of Natural Resources and Environment. In 2018, Ban Tak Petrified Forest Park was included within 35,542 hectare Doi Soi Malai National Park, which includes a large area of modern tropical forest. The fossil forest occurs in an area of ~2000 hectares. More than 40 fossil logs are known to be preserved within the fluvial sediment, but only 7 have been excavated (Table 1).Based on taxonomic study, all were angiosperms, representing two types of legume trees: *Koompassioxylon elegans* Kramer and *Pahudioxylon* cf. *sahnii* Ghosh & Kazmi [3].

Figure 2. Tak fossil logs. BT-1 is shown in a newly-constructed permanent shelter. This log is relatively well preserved. Logs 2–5 are highly fragmented.Logs 6, 7 have fractured areas, but are mostly intact.

Table 1. Ban Tak specimen list. Data adapted from [4]. Density values determined as part of our research.

Fossil Log	Specimen for Analysis	Density * gm/cm^2	Taxonomy	Length (m)	Diameter at Mid Length (m)	Current Preservation
BT-1	BT1	2.33	*Koompassioxylon elegans*	69.7	1.8	Mostly intact with cracks along the trunk. Some surface fragments, especially in lower middle region, Severe erosion of the butresss
BT-2	BT-2	2.48	*Pahudioxylon* cf. *sahnii*	31.1	0.5	Fragmented
BT-3	BT-3	2.11	*K. elegans*	32.4	2.1	Fragmented
BT4	BT-4a	2.31	*K. elegans*	44.2	1.4	Fragmented
	BT-4b	2.36				
BT-5	BT-5a	2.31	*Pahudioxylon* cf. *sahnii*	22.2	31.3 32.4 44.2	Partially fragmented, especially in the middle zone. Buttress in large pieces with many cavities
	BT-5b	2.31				
	BT-5c	2.42				
BT-6	BT-6	2.34	*K. elegans*	34.5		Mostly intact, locally fragmented
BT-7	BT-7	2.38	*K. elegans*	38.7	22.2	Mostly intact, but buttress partially collapsed and weathered
Mean density		2.34				

* Density values from this report.

3.1. Geologic Setting

Ban Tak Fossil Forest is located in a basin covering parts of the Ban Tak and Sam Ngao districts in Tak Province. The basin is underlain by granitic rocks, a convergence of several episodes of intrusion during the Triassic, comprising white leucocratic granite and pink biotite granite. Individual pluton compositions include quartz diorite, granodiorite, quartz monzonite, and granite. The highlands on the western border of the basin are mostly composed of Precambrian metamorphic rocks that include mica schist, gneiss, and calc-silicate rocks. A chain of granitic mountains forms the eastern border [3]. The fossil logs are located approximately 8 km downstream from the confluence of the Ping and Wang Rivers (Figure 1). This geologic framework has significance for the origin of the silicified logs: Volcanicglass in the form of lava flows or tephra potentially provides a source of dissolved silica for wood silicification, but weathering of surface exposures of felsic intrusive rocks may also provide a source. At Ban Tak, tree trunks were buried under fluvial sediments rich in rhyolitic tuff debris that the Wang River carried from the Permo-Triassic andesitic-rhyolitic volcanic rocks situated less than 20 km north of the Ban Tak Petrified Forest Park [5]. Because quartz is relatively insoluble, Si probably came from the breakdown of feldspar or other aluminosilicate minerals. Indeed, feldspar has been mined commercially in the hills bordering the river valley [6]. The fossil logs were recognized as Pleistocene, with a preliminary age estimate of approximately 800,000 years based on stratigraphy, e.g., the gravel is locally overlain by aasalt flow having an age of between 0.6 $\pm$ 0.2 and 0.8 $\pm$ 0.2 Ma [3,7]. Later thermoluminescence dating yielded more precise age estimates. Gravel enclosing logs 1, 4, and 5 had TL ages of 50,000–53,000 y with ages of 20,000–23,000 y for sediment surrounding logs 6 and 7. Reported TL ages for Tak silicified wood range from 120,410 $\pm$ 12,342 y to 185,800 $\pm$ 9852 y [8–11]. Despite the dating discrepancies, the age of the logs is clearly Pleistocene. They appear to be many thousands of years older than the sediment that presently encloses them. Perhaps these discrepancies are a result of analytical error. Alternately, the sediments have been reworked so that younger material has replaced some of the original sediment.

Ancient sedimentary deposits in the Ban Tak-Sam Ngao Basin include lag gravels, channel bars, and alluvial fans. Debris flows from the adjacent hill slopes provided an abundant source of coarse clastic sediment. The main basin presently contains the south-flowing Ping River, the smaller Wang River. Construction of two dams in the northern part of the basin have blocked upstream sediment supply and changed downstream sedimentation patterns, but gravel deposits near the dams contain clasts up to 12 cm in diameter, evidence of high flow velocity. Sediment sizes at the Ban Tak Petrified Forest area are finer, comprised of gravel and sand. The orientations of fossil logs suggest that they originated as driftwood on channel bars and on alluvial fans draining from tributary streams [3].

Small specimens from the 7 Tak fossil logs were used for mineral analysis (Figure 3).

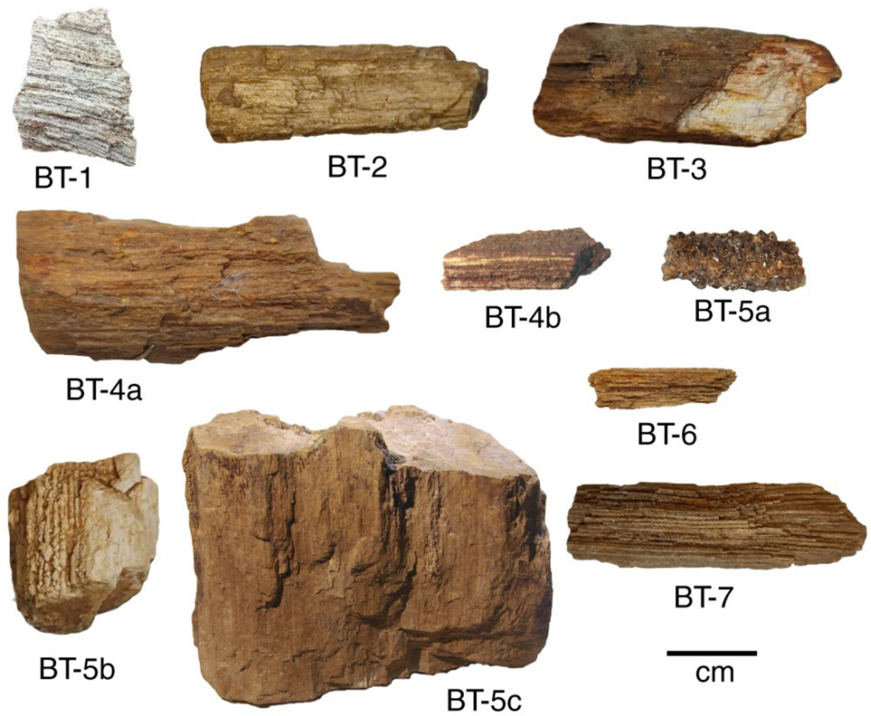

Figure 3. Ban Tak specimens used in this study.

3.2. X-ray Diffraction Data for Tak Fossil Wood

XRD patterns show that quartz is the only detectable crystalline material in unweathered specimens (Figure 4). Weathered regions may also contain clay minerals and iron oxides [9–11].

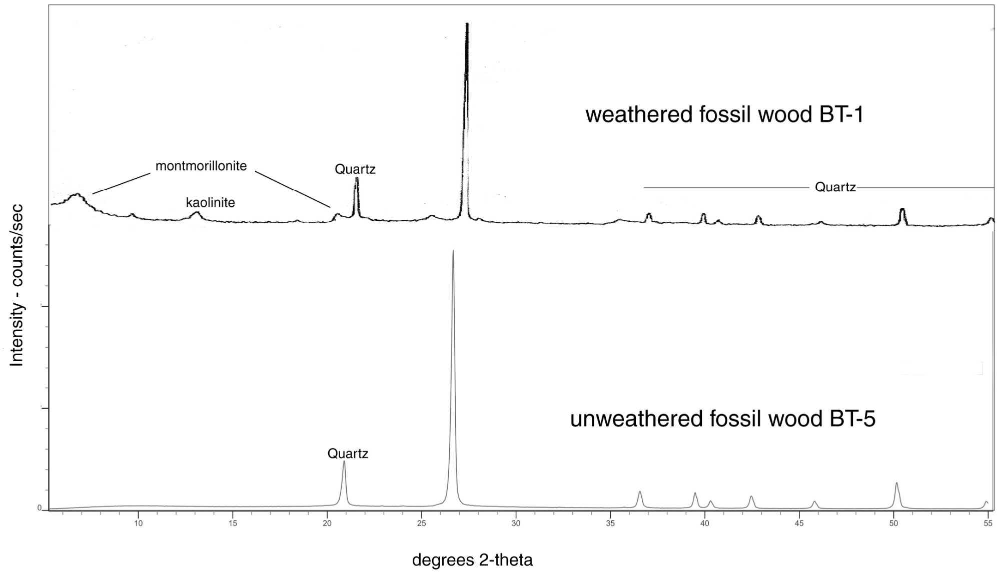

Figure 4. XRD pattern, specimen BT-5c, showing quartz as the only detectable constituent compared to weathered outer zone of BT-1, which shows presence of montmorillonite, illite, and quartz. This weathered zone also contains amorphous iron oxide, not detectable by XRD.

3.3. Microscopy of Tak Fossil Wood

Optical photomicrographs and SEM images (Figures 5–9) show that macrocrystalline quartz is the predominant component of fossil logs, but opalized cells are present in some specimens (Figure 7). The fossil wood is typically not fully mineralized, causing longitudinal grain patterns to be visible to the unaided eye. Fracture planes and other open spaces may contain well-terminated quartz crystals (Figure 7). The relatively low densities of silicified wood specimens (Table 1) are indicative of incomplete mineralization; quartz-mineralized wood commonly has densities in the range of 2.5 to 2.6 g/cm^3 [4].

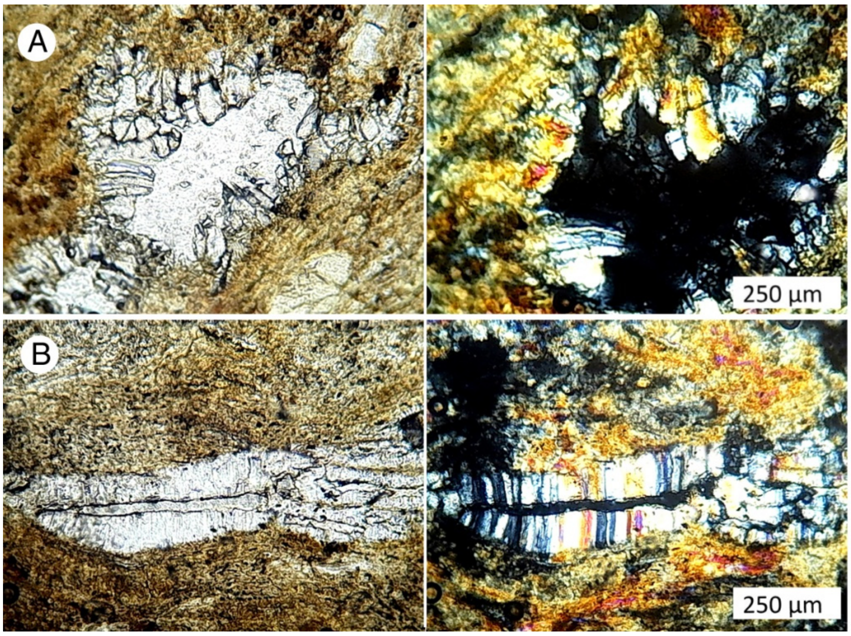

Figure 5. Thin-section images of fossil wood from Tak fossil forest showing vessels lined with quartz crystals, with the central area remaining open. For each pair, the image on the left is illuminated with ordinary transmitted light; the image on right was made with cross-polarized light. (**A**) Specimen from log BT-3. (**B**) Specimen 4c, collected from log BT-4.

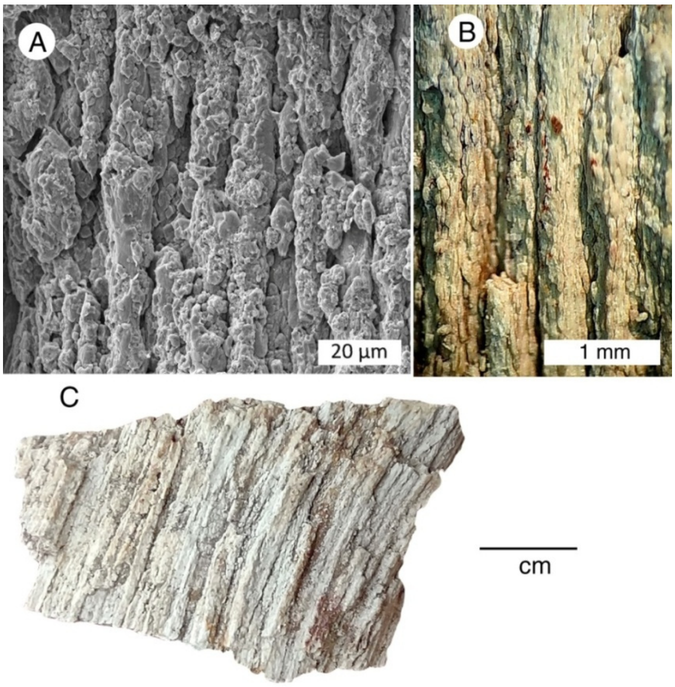

Figure 6. Tak fossil wood from log #1. (**A**) SEM view of longitudinal surface. (**B**) Low-power optical microscope image. (**C**) Specimen showing cells coated with quartz crystals. All images show incomplete mineralization, where intercellular spaces remain open.

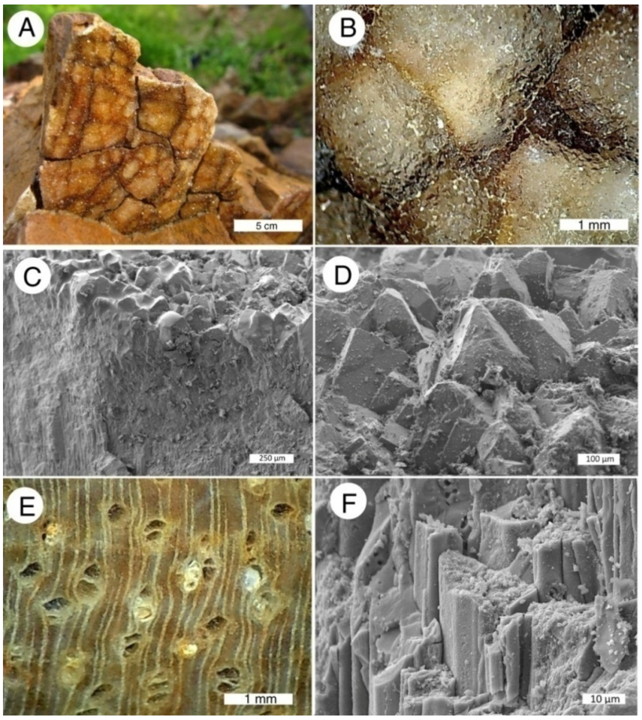

Figure 7. Tak fossil log BT-5, specimen 5c. Fracture surfaces show a layer of euhedral quartz crystals covering wood that is mineralized with opal. (**A**) Field view. (**B**) Low power optical microscope image. (**C**) SEM image showing crystal coating on opalized wood, oblique longitudinal view. (**D**) SEM image of quartz layer, oblique radial view. (**E**) Thin-section optical microscope image, Transverse orientation showing opal mineralized wood with most vessels remaining open. (**F**) SEM image, longitudinal view of opalized cells. Cell lumens are fully mineralized, but intercellular spaces commonly remain open.

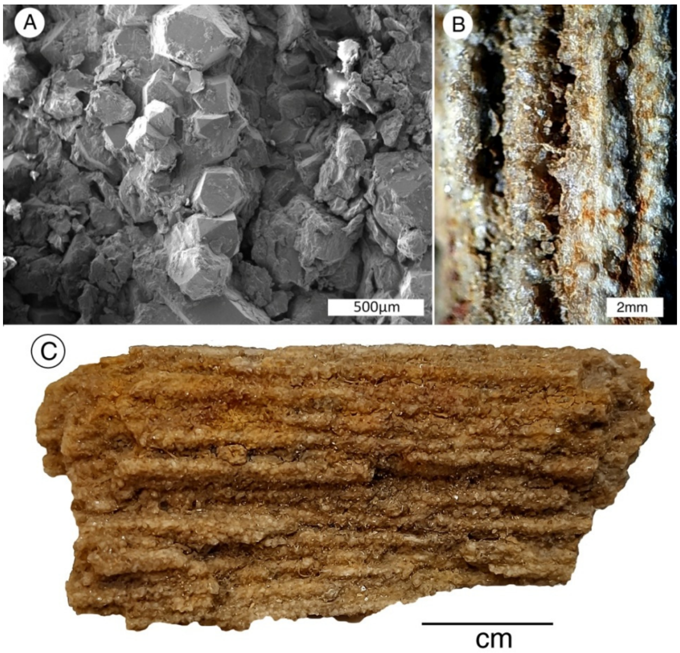

Figure 8. Quartz-mineralized wood from Tak log BT-6.Cells are coated with quartz crystals, but incomplete mineralization is evidenced by partially open intercellular spaces. (**A**) SEM image of subhedral quartz crystals coating individual cells, longitudinal orientation. (**B**). Low magnification optical microscope photo showing open intercellular spaces between crystal-coated cells. (**C**) Quartz crystals coating wood fibers are large enough to be seen with the unaided eye.

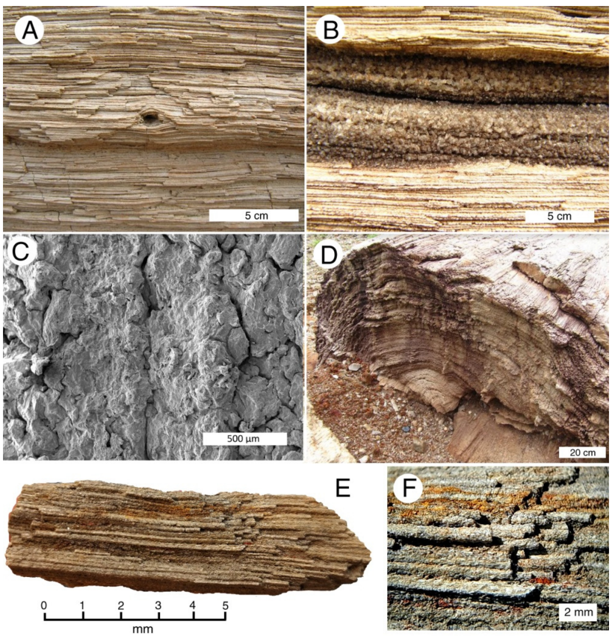

Figure 9. Quartz-mineralized wood from Tak log BT-7. Individual cells are coated with subhedral quartz crystals, with incomplete mineralization of intercellular spaces. (**A**) Field photo showing wood grain pattern. (**B**) Zone where quartz crystals are relatively large. (**C**) SEM image, longitudinal orientation. (**D**) Transverse view of log #7 fracture. Mineralization produced brittleness that allowed cross-grain fracture but partially open intercellular spaces resulted in an uneven surface. (**E**,**F**) Crystalline texture is readily apparent, but absence of mineralization of intercellular spaces allows individual wood fibers to be visible.

4. Khorat Fossil Wood

Fossil wood is abundantly preserved in the river channel and terrace sediments along the tributaries of the Mekong River, in the Khorat plateau in Nakhon Ratchasima Province (Figure 10). Hundreds of petrified logs were discovered during construction of the Mittraphap Highway (a.k.a Friendship Highway) due to the use of large amounts of gravels from Khok Kruat and Suranaree subdistricts, Mueang Nakhon Ratchasima. Tons of surface sediment were removed, exposing petrified logs that ranged from 1 to 10 m in length with diameters of 10–80 cm. Unfortunately fossils were removed and sold throughout the country and overseas for decades. Beginning in 1994, cooperation between private and government sectors of Nakhon Ratchasima Province resulted in a petrified wood conservation program administered by the Northeastern Research Institute of Petrified Wood and Mineral Resources, under the auspices of Nakhon Ratchasima Rajabhat University. Construction of the Khorat Fossil Museum (later renamed as Northeastern Institute of Petrified Wood and Mineral Resources) was completed in 2002, and opened to the public in 2004, formally opened in 2008. In addition to the indoor exhibits, fossil logs are displayed in outdoor garden setting. A nature trail allows visitors to see at least five ancient logs in their original horizontal position. In addition to fossil wood, the museum displays a diverse collection of vertebrate fossils from northeastern Thailand, ranging from dinosaurs to Ice Age mammals.

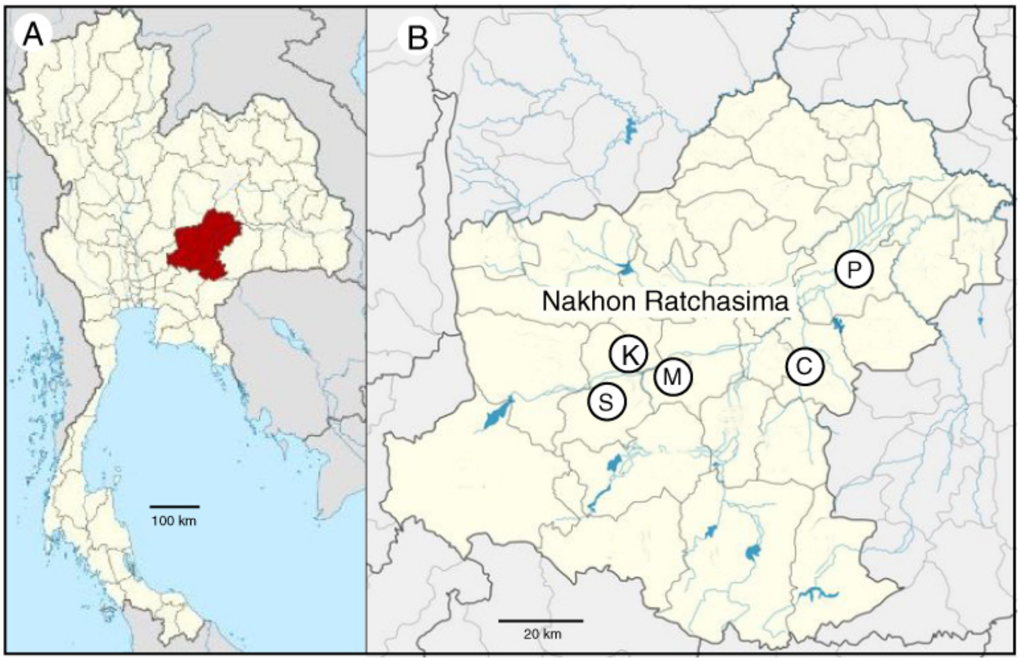

Figure 10. Maps showing Khorat Plateau fossil wood localities used in this study. (**A**) Thailand map showing Nakhon Ratchasima Province in red. (**B**) Specimens came from five districts within theprovince:C = Chakkarat, K—Kham Thale So, M = Mueang Nakhon Ratchasima, P = Phimai, S = Sung Noen.

Mineralogy was determined for 11 fossil wood specimens from Nakhon Ratchasima Province (Figure 11, Table 2).

Figure 11. Khorat Plateau fossil wood specimens used for this study, showing specimen numbers. Samples are from Nakhon Ratchasima Province, except S-8, which is from Kohn Kaen Province.

Table 2. Density and mineral composition of fossil wood specimens from locations in Nakhon Ratchasima Province.

Specimen	Location		Density g/cm^2	XRD	Thin Section Mineralogy
	District	Subdistrict			
S-1	Chakkarat	HinKhon	2.59	quartz	quartz, chalcedony
S-2	Kham ThaleSo	Pong Daeng	2.00	opal-CT	opal A, opal-CT
S-3	Mueang Nakhon Ratchasima	Suranaree	1.99	opal-CT	opal-A, minor opal-CT
S-4	Mueang Nakhon Ratchasima	Suranaree	2.10	opal-CT	opal-A, minor opal-CT
S-5	Mueang Nakhon Ratchasima	Suranaree	2.09	opal-CT	opal A, minor opal-CT
S-6	Chakkarat	HinKhon	2.56	quartz	quartz
S-7	Mueang Nakhon Ratchasima	Suranaree	2.59	quartz	quartz, minor chalcedony
S-8	Mueang KhonKaen	Sawathi	2.33	quartz	quartz
S-9	Sung Noen	Ma Kha	2.56	quartz	quartz, chalcedony
S-10	Mueang Nakhom Ratchasima	NongRawiang	2.45	quartz	quartz
S-11	Phimai	RangkaYai	2.46	quartz	quartz, minor chalcedony

4.1. Geologic Setting

The Khorat Plateau incudes approximately 1/3 of Thailand, extending into western Laos, and part of Cambodia. Elevations range from 130 to 1326 m above sea level, with an average elevation of 238 m. Basin evolution was related to an extensional zone that resulted from the India-Eurasia plate collision. Part of the Indochina terrane, the plateau has been undergoing uplift since the late Cenozoic. The Khorat Plateau has a width of ~400 km, consisting of gentle topography bordered on the western and southern rim by Mesozoic sandstone. The plateau is divided into two basins by the Phu Phan Range, creating the Sakon Nakhon Basin in the north, and the southern Khorat Basin. The latter basin contains the Chi and Mun Rivers, tributaries of the Mekong River that forms the border between Thailand and Laos [12].

The bedrock of the Khorat Plateau consists of a thick sequence of Mesozoic sediments that are underlain by Paleozoic strata. The plateau is largely covered by soil and alluvial sediments that include clay, silt, sand, and gravel (Figure 12). The bedrock stratigraphy is known from outcrops along the perimeter of the plateau and in the Phu Phan Range, supplemented with data from wells drilled for petroleum exploration. Mesozoic strata range in age from late Triassic to Cretaceous. They are an important source of fossils. Jurassic outcrops include sandstone, siltstone, and mudstone layers that preserve both invertebrate and vertebrate fossils and plant remains [13]. Overlying Cretaceous strata include channel and floodplain deposits from a meandering river, a paleoenvironment that was inhabited by dinosaurs, fish, crocodylians, and turtles, which are all evidenced by the fossil record [14].The Cretaceous beds also preserve numerous silicified trunks [15–19].

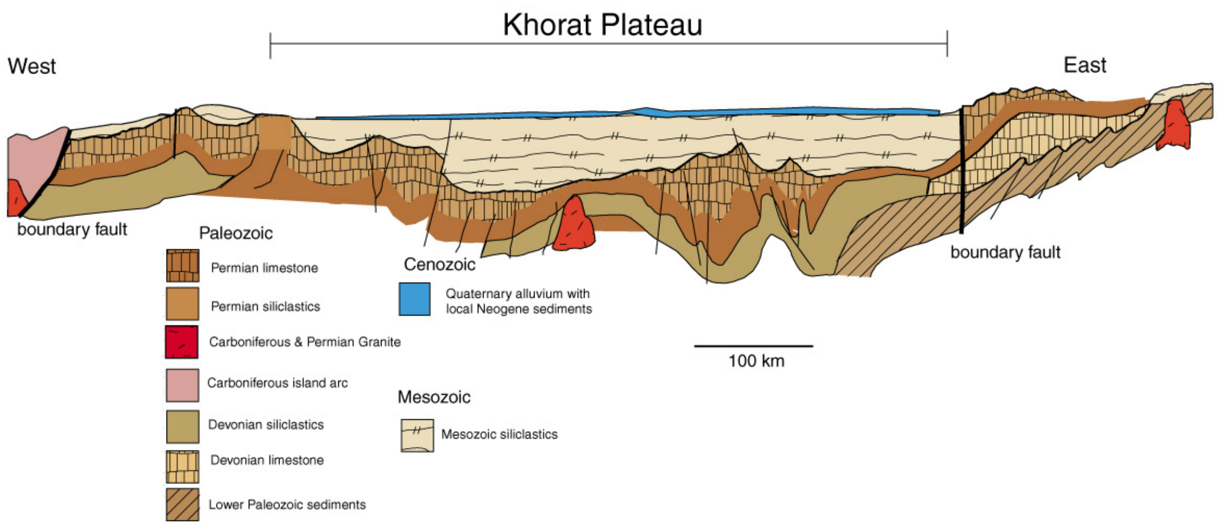

Figure 12. Generalized cross-section of the Khorat Plateau. Fossil wood occurs abundantly in Neogene alluvial fan deposits and Quaternary fluvial sediments that thinly cover large areas of the region.

Cenozoic fossil wood is abundantly preserved in Pleistocene gravelly sediments deposited along the Mun River, a major Mekong River tributary. Vertebrate fossils in these alluvial deposits range in age from Miocene to Pleistocene, suggesting that ages of silicified wood specimens are variable.Beginning in 1956, gravel and sand began to be extensively mined for use in road and airport construction, the main sites being Khao Din (Ban NongRanka) and Khao Kaew (Ban KrokDuean Ha). These mining operations produced thousands of specimens of petrified wood, some quite large. Most fell into the possession of private collectors or were sold commercially both nationally and internationally. Petrified wood specimens were commonly found in sand pits where the extraction processes prevented recognition of taphonomy and stratigraphic position of the individual fossils.

Prakash [20] identified five taxa of fossil wood collected during a forestry project, from depths of 1–50 m below the surface from sandstone and laterite. Taxonomy of Mesozoic woods from Khorat was reviewed by Wang et al. [21]. In contrast to the gymnosperms found in Mesozoic strata, Cenozoic woods at Khorat are dominated by a diverse variety of angiosperms. *Palmoxylon* is the only known monocotyledon taxa. Eight dicotyledonous families have been identified, comprising 16 genera represented by about 40 species [20].

At most Khorat localities, fossil woods are well-silicified, but a sand pit in eastern Nakhon Ratchasima Province has yielded specimens that contain large amounts of relict organic matter [22].

4.2. Composition of Khorat Fossil Wood

Fossil woods from the Khorat Plateau have a diverse range of compositions, varying from pure quartz (Figures 13 and 14) to pure opal (Figures 15 and 16), with some specimens containing both silica polymorphs. SEM images included in Figures 13 and 15 provide detailed views of the mineral phases. XRD patterns included in these plates show the distinctive differences between quartz and opal, in contrast to XRF spectra that are similar for both minerals Figure 13D). Petrographic thin sections revealed the presence of quartz, chalcedony, and opal in Khorat fossil wood (Figure 14). Opal includes both amorphous opal (opal-A) and opal-CT, a form with incipient cristobalite/tridymite crystallinity (Figure 15).

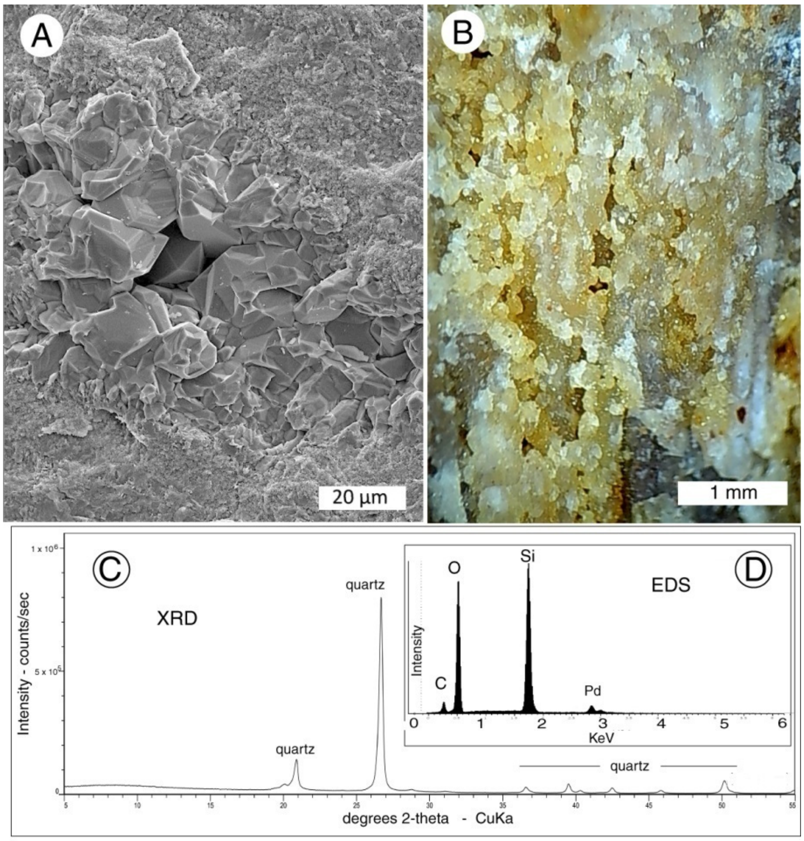

Figure 13. Sample S-1, an example of fossil wood that contains quartz as the only major constituent. (**A**) Scanning electron microscopy showing that vessels commonly contain quartz crystals, in contrast to the fine-grained quartz that has replaced surrounding tissue. (**B**) Low-magnification optical microscopy shows the replacement of individual wood cells by crystalline silica. (**C**) XRD pattern consists only of quartz peaks. (**D**) In the SEM/EDS spectrum, the small carbon peak is evidence that the fossil wood contains only a very small fraction of the original organic matter. The Pd peak is from metal applied to the SEM specimen to prevent electrical charging.

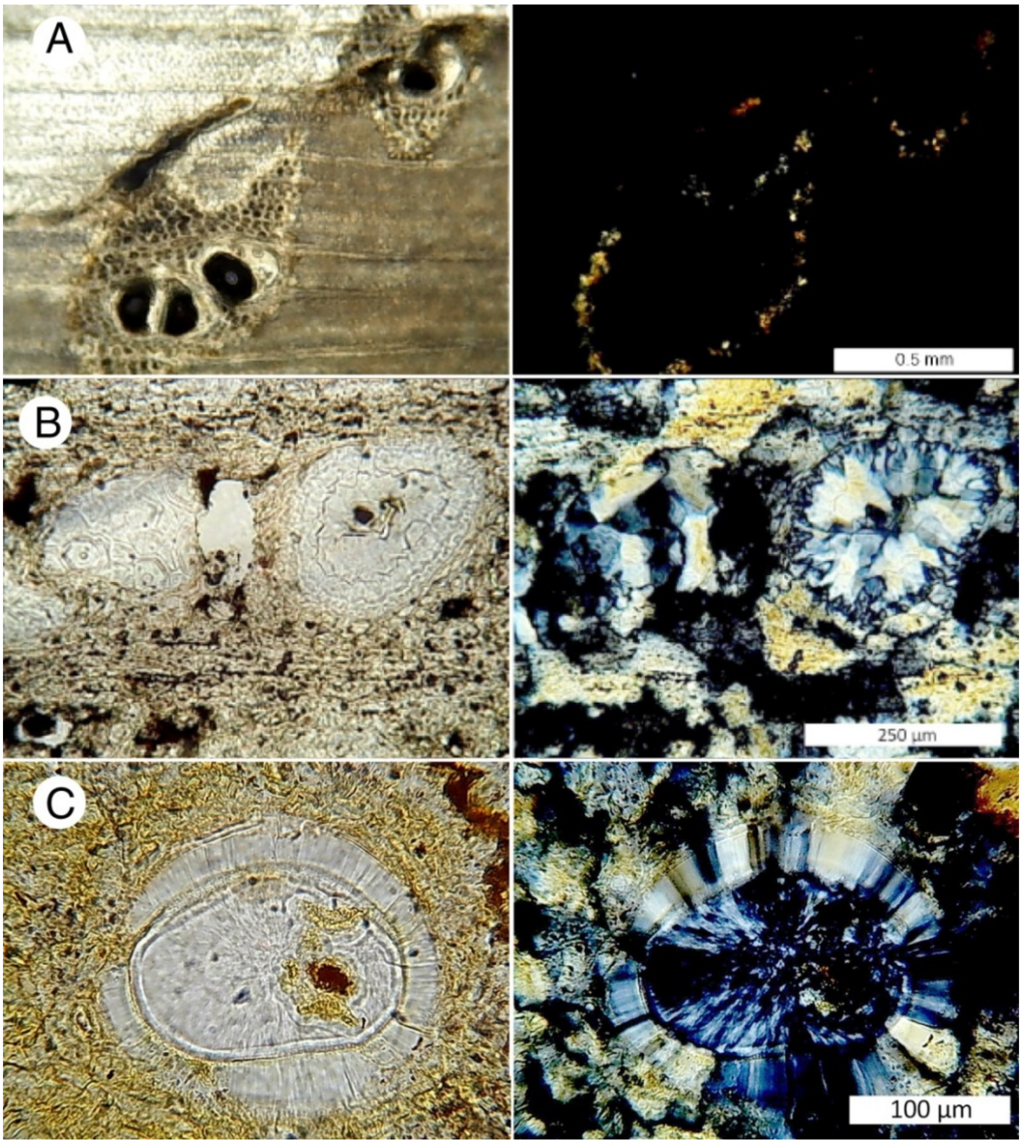

Figure 14. Petrographic thin sections showing mineral variations in Khorat specimens (transverse views). Each photo pair shows ordinary transmitted light illumination on the left, crossed polarized light at right. (**A**) Specimen S-2 is predominately composed of opal-A, which is black (isotropic) under polarized light. Opal-CT is visible as a narrow band. (**B**) Specimen S-10, showing a pair of vessels in wood mineralized with crystalline quartz. (**C**) Specimen S-11.Vessel wall and peripheral cells are mineralized with chalcedony. The surrounding tissue has been replaced by fine-grained quartz.

4.3. Forms of Opal in Khorat Wood

SEM images show the incipient crystallinity of opal-CT.Tabular crystal clusters commonly occur in areas where open space allowed development of well-formed shapes (Figure 16). Many of these voidsnow contain opal-CT layers that have botryoidal textures. Surrounding vitreous areas may consist of either opal-CT or opal-A. Discrimination between these two forms of opal may be difficult in SEM images. More reliable identifications can be made by polarized light optical microscopy, because amorphous opal-A is isotropic, while the incipient crystallinity of opal-CT produces weak birefringence.

4.4. Forms of Quartz in Khorat Fossil Wood

Similar to the occurrence of opal-CT, euhedral quartz crystals are found in voids where space allowed the formation of terminated crystals (Figure 17). This crystallization results from slow precipitation of silica from relatively dilute solutions, allowing time for SiO_2 molecules to form well-ordered lattices.

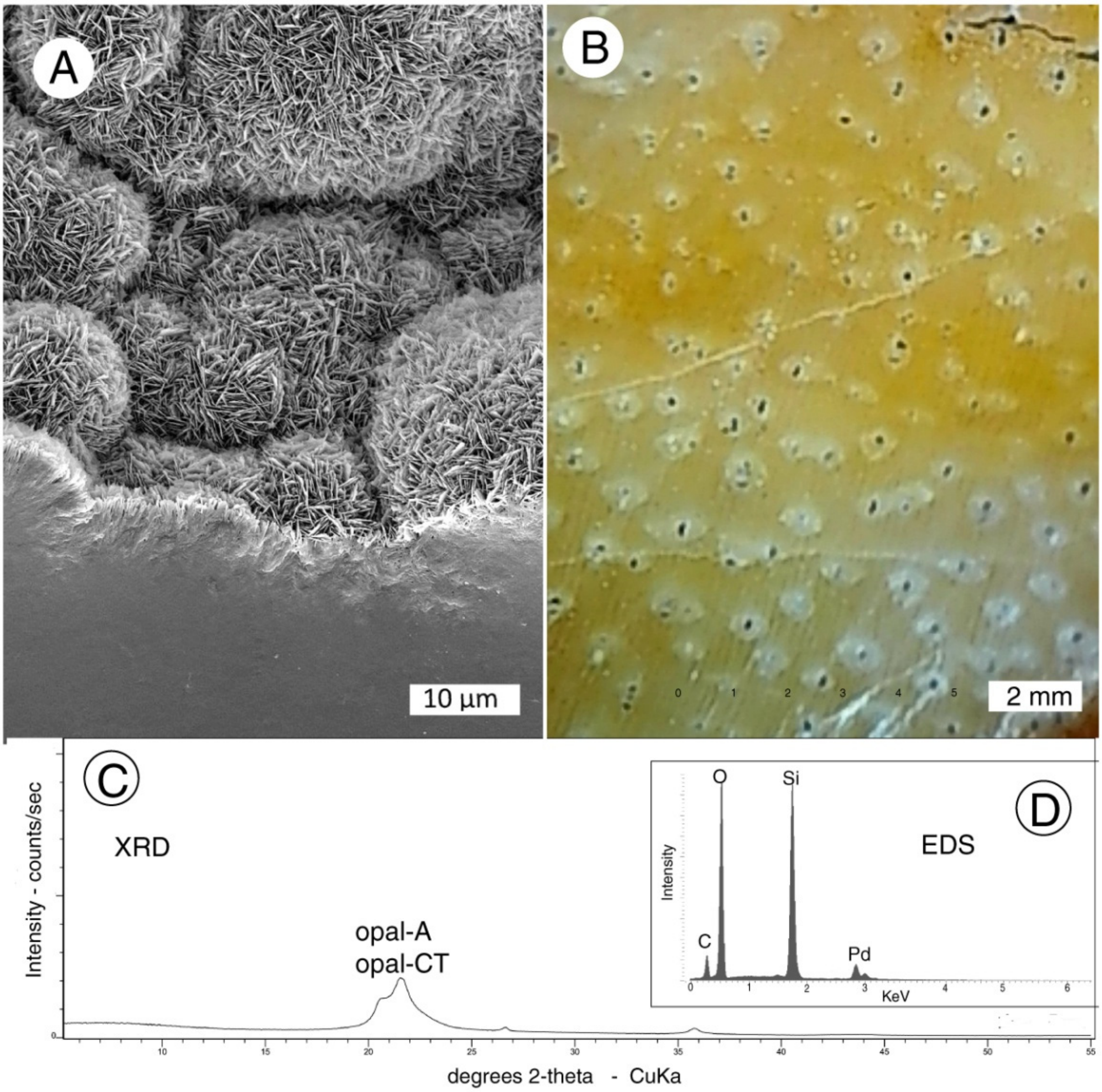

Figure 15. Microscopy and XRDS analysis of sample S-2 showing opal mineralization. (**A**) SEM image shows crystalline opal-CT lining a cavity. Adjacent smooth areas are presumably amorphous opal-A. (**B**) Transverse orientation shows preservation of vessels, evidence that this is angiosperm wood. (**C**) XRD pattern shows diffuse peaks characteristic of opal-CT. The very weak peaks of opal-A are obscured by the opal-CT peaks, but the overall low intensity of the diffraction pattern suggest that opal-CT is not the major constituent. (**D**) The SEM/EDS spectrum is nearly identical to that of specimen S-1, evidence that the X-ray fluorescence data do not distinguish between quartz and opal because both consist of SiO_2. The inability to detect the presence of H precludes the possibility of recognizing hydrous opal.

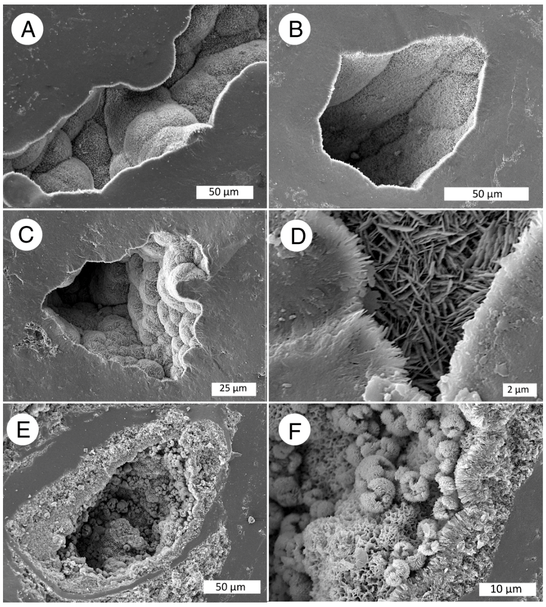

Figure 16. SEM images of opalized wood. (**A**) Sample S-4 showing botryoidal opal-CT lining a small cavity. (**B**) Sample S-4, oblique transverse view of opal-A mineralized wood with a vessel that contains a thin lining of opal-CT. (**C**) Similar features are present in sample S-3. (**D**) High magnification view of opal-CT in sample S-2, showing bladed crystals. (**E**,**F**) Vessel containing hemispherical masses of opal-CT lying on a botryoidal opal-CT layer. The smooth surrounding material is opal-A.

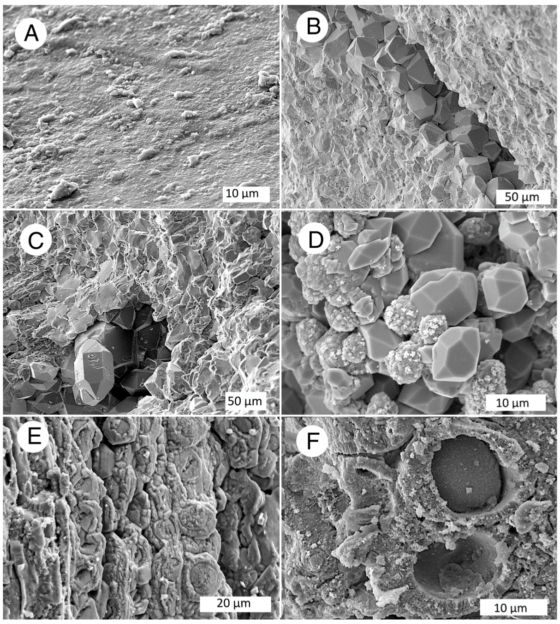

Figure 17. SEM images of Khorat specimens mineralized with quartz/chalcedony. (**A**) Sample S-5, transverse view showing homogeneous quartz. (**B**) A small fracture in sample S-7 is lined with euhedral quartz crystals. The surrounding matrix is microcrystalline. (**C**) Sample S-7 shows a similar structure, where a vessel is lined with euhedral quartz crystals, enclosed by quartz having smaller crystallinity. (**D**) A vessel in sample S-8 has an unusual combination of quartz dipyramids and silica particles having a granular surface texture. This morphology was observed in no other specimens, and the origin is enigmatic. (**E**) Longitudinal view of sample S-10 shows preservation of pit morphology in wood mineralized with quartz. (**F**) Vessels in sample S-6 are lined with chalcedony, with lumen remaining open. Similar chalcedony mineralization can be seen in the thin section photo for sample S-11 (Figure 15C).

5. Wood Fossilization Processes

Silicification of wood may follow a variety of mineralogic pathways [23], but some generalizations can be made. The quality of anatomical preservation is related to the relative rates of mineral precipitation and tissue degradation. Rapid mineral precipitation may entomb intact cells to produce "permineralization", a phenomenon that is common in calcite mineralized wood [24] but relatively rare in silicified wood [25]. A common pathway is for silica-bearing groundwater to be absorbed into buried wood, a process that is facilitated because the structure of wood has evolved to optimize transport of water. Initially, silica molecules will bond to organic materials in the cell wall, a phenomenon known as *organic templating* [26]. This rapidly-precipitated silica will be amorphous. The incipient amorphous silicification of cell walls may be followed by precipitation of silica in cell lumen and intercellular spaces. For angiosperms, water conduction primarily occurs in vessels, and these relatively large-diameter cells may be among the last spaces to mineralize. Lacking vessels, gymnosperms rely on hollow tracheids for fluid transport. For both wood types, open spaces created by fractures or rot pockets may be the last spaces to become mineralized.

The form of silica that is precipitated depends primarily on dissolved silica levels. High Si concentrations are likely to result in rapid precipitation where orderly lattices do not have time to develop. The result may be amorphous opal-A. Weakly crystalline opal-CT may be a primary precipitate, or a subsequent alteration product of opal-A. Formation of chalcedony typically results from lower levels of dissolved Si, where slow precipitation rates allow the development of well-ordered lattices. For chalcedony, the cryptocrystalline structure consists of fiber-like particles. In contrast, quartz is characterized by hexagonal crystals varying in size from microscopic to megascopic. Crystal texture may not be visible to the naked eye (e.g., massive quartz), but larger crystals may be readily apparent. Well-terminated crystals are a special case, requiring open space to develop. This explains the common occurrence of fossil wood where euhedral or subhedral quartz crystals line the walls of vessels or fractures with terminations that point toward the cavity. Finally, the mineral composition may gradually change during prolonged burial, e.g., when opal transforms to chalcedony. In summary, the final mineral composition represents a combination of botanical architecture, primary precipitation effects and subsequent diagenetic changes.

The degree of anatomical preservation is related to the mineralization history. As noted above, complete preservation of wood tissue (permineralization) is infrequent. Far more commonly, the process of mineralization occurs simultaneously with cellular degradation. If wood decomposition is fast, the resulting fossil may simply be a cast that preserves the external surface texture, but no internal anatomy. When mineralization and decomposition are in approximate balance, the result will be silicified wood where the cellular anatomy is mimicked by color variations within the silica.

5.1. Tak Wood Fossilization

At Tak, the wood is primarily mineralized with crystalline quartz as a result of high levels of dissolved silica in groundwater that permeated alluvial sediment surrounding buried driftwood logs. Worldwide, the source of soluble silica is typically either from volcanic glass (e.g., tephra or lava flows), or dissolution of feldpathic silicates, particularly feldspar [27,28]. The presence of volcanic materials in Tak Province and the widespread occurrence of granitic plutons suggest that breakdown of felsic minerals was the source of high Si levels in regional groundwater. This silicification is evidenced both by the fossil wood and by local silica cementation of the gravel to produce conglomerate [3].

Tak fossil woods have two notable mineralogic characteristics. First, the individual wood fibers have been replaced by quartz. Second, spaces between cells (intercellular spaces) commonly remain unmineralized. In some specimens, this results in a pattern of crystallinity where subhedral or euhedral quartz crystals radiate outward from the individual wood fibers.

This unusual mineralization accounts for the lack of resistance of the fossil wood to weathering. Several factors are involved. Most important, open intercellular spaces cause the wood to split along radial and tangential planes. In modern wood, splitting resistance is largely the result of the presence of intermedullary ray cells, which provide lateral strength. Mineralization of ray cells may cause them to be brittle, and they lose their directional strength. Similarly, longitudinal cells become brittle. Fossil wood therefore lacks the elastic quality typical of living trees, where flexibility is an important asset for surviving wind storms. The rigidity of silicified wood is evidenced by the tendency of the wood to develop transverse ("cross-grain") fractures (Figure 18). These fractures are common in silicified logs at Tak. The forces that produced these features may be tectonic (e.g., stresses related to local faults) or changes in the geometry of the alluvial sediments that enclose the log. For example, compression of sediments from gravity or volume changes caused by hydration or dehydration might have changed the foundational support of the buried fossil logs. Segmentation of a log by transverse fracturing increases the vulnerability of the wood for longitudinal splitting. Fracturing is perhaps related at least in part to past seismic activity. Because of collisional tectonic history, Thailand is a seismically active region, and Tak is one of the provinces that has the highest risk of earthquakes [29–32]. The combination of the above affects has caused some logs to become highly fragmented (Figure 2).

Figure 18. Transverse fractures in Tak logs. (**A**,**B**) BT-1. (**C**,**D**) BT-7.

The incomplete mineralization of Tak fossil wood is very evident during preparation of petrographic thin sections, because the wood cuts very rapidly with a diamond lapidary blade, in marked contrast to the slow cutting rates for wood that is completely mineralized with chalcedony or quartz. As noted previously, open intercellular spaces are observable in optical microscope and SEM images (Figures 6–9).

The presence of open intercellular spaces gives rise to other possible causes of wood deterioration. When these spaces contain clay or other weathering products (as evidenced by XRD patterns, Figure 4), changes in moisture levels may cause swelling/shrinkage cycles that result in mechanical stress [9]. This is of particular concern because of the monsoon weather patterns characteristic of Indochina. Also, the precipitation of iron hydroxides or inhabiting of these spaces by microbes may result in discoloration of the wood. Quantitative microanalyses by Saminpanya [9] documented this effect. High Fe levels are typical of woods that have orange or red color, with lower Fe levels in white, gray, and brown woods. Aluminum levels do not show a close correspondence to wood color, which is not surprising because this element is not important as a colorant for silicified wood [31]. The presence of microbes in Tak wood [32,33] has been inferred to be the result of microfractures that allowed permeation of water into the silicified tissue. Microbial growth may be a cause of discoloration.

5.2. Khorat Plateau Wood Fossilization

Khorat fossil wood typically shows complete mineralization, unlike the open intercellular spaces typical of Tak wood. Another difference is the varied composition, with woods containing pure quartz, mixtures of opal-A and opal-CT, and mixtures of quartz and chalcedony (Table 2). These mineral variations suggest that silicified wood found in Quaternary sediments was petrified via diverse geochemical processes. Factors may have included variations in dissolved silica concentrations, pH, or temperature. Local highsilica concentrations may have been caused by a hydrothermal solution that travelled along fractures in the bedrock rock layer to reach sediment layers that contained buried logs.

6. Conservation Issues

Ideally, conservation strategies would be developed before fossil buried logs are fully excavated, but in practice this approach has limitations. The physical state and mineral composition of logs cannot be determined until the fossils are excavated. Also, an important first step in preservation is to provide legal protection for the site, and funding for conservation efforts. These efforts require public awareness that comes from exposed specimens.

Much conservation work has been conductedfor archaeological and architectural materials, with only a few published descriptions of conservation strategies for fossil wood. These include reports from Lesvos Petrified Forest in Greece [34], Florissant Fossil Beds National Monument USA [35–37], and Bukkábrány, Hungary [38]. Thailand fossil forests provide the first example of conservation actions developed for a tropical environment [10,39,40]. We provide an overview of these strategies.

Thailand's climate is characterized by three seasons: six months of heavy monsoon rainfall, three months of summer heat, and three months of dry, cool winter. Effective conservation strategies must accommodate these variable conditions. Adding to the complexity, fossils from different sites and even within different parts of a single fossil log may have variations in physical and chemical properties, different mineral composition, and be subject to differing environmental factors. These challenges mean that conservation strategies need to be based on empirical evidence.

Macroclimate and Microclimate Measurements

Climate data have been recorded at Tak since 2017. Microclimate measurements were made by placing 20 data loggers within fractures or other open spaces at various locations within petrified trees, typically 2–3 data loggers per trunk. These records show that relative humidity, dew point and temperature vary widely even in fossils that are inside protective shelters (Figure 19).

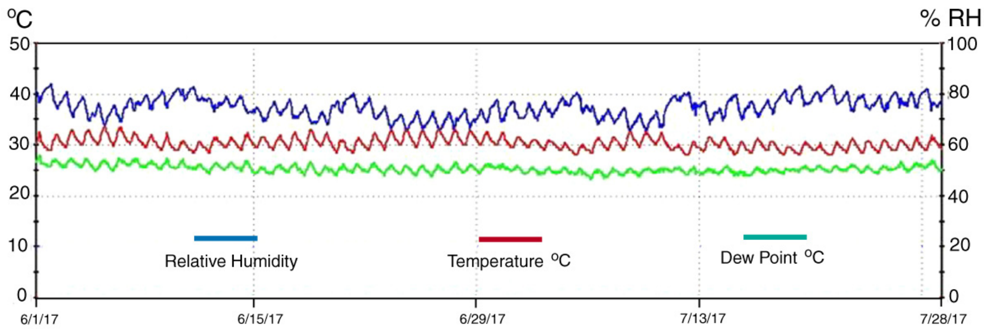

Figure 19. Microclimate variations in fossil log BT-1, recorded during early rainy season, 2017. The log was in a temporary shelter. Measurements were made at a length of 68 m from the base of the trunk [10].

These variations are significant because moisture plays a key role during the weathering of Tak logs.As noted previously in this report, incomplete mineralization of the wood produces open spaces that provide conduits for adsorbed water and allow introduction of secondary minerals. Iron solubolized from minerals in adjacent sediment precipitates within the silicified wood to cause patchy yellowish, reddish, or brownish discoloration (Figure 20). Quartz is not a parent material for clay because of the low solubility and the absence of aluminum and alkaline elements, which are essential materials for clay mineral genesis. Decomposition of silicate minerals in the surrounding sediment likely provided parent materials for clay minerals that occur within the fossil logs. These weathering products are concentrated near the surface, producing a weakened weathered crust.

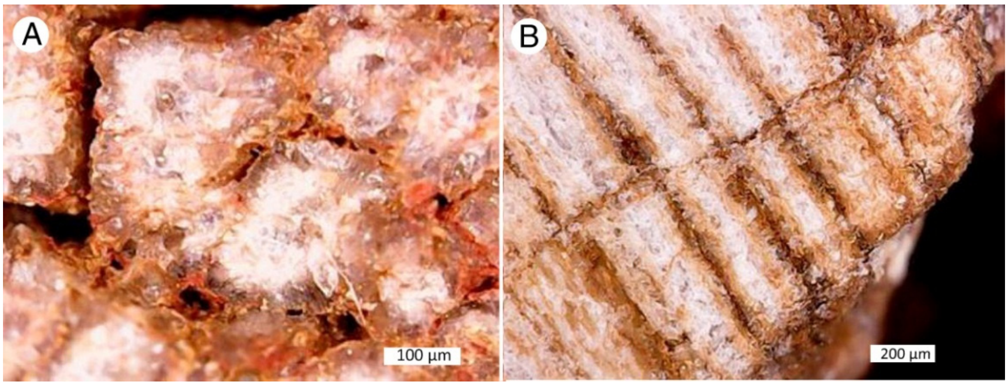

Figure 20. Iron oxide stains are concentrated where Fe-bearing solutions entered intercellular spaces between fiber cells and parenchyma tissue surrounding vessels. (**A**) Transverse view. (**B**) Longitudinal view.

Five basic approaches for Thailand fossil forest sites are (1) removal of specimens so they can be displayed indoors, (2) construction of shelters to retard weathering rates, (3) adjusting excavation topography to avoid V-shaped trenches that allow drainage water to collect near the logs, (4) application of consolidants or water repellants to increase the resistance of specimens to weathering, (5) use of adhesives to repair specimens that have become fragmented. Mechanical reinforcement methods such as external metal bands or internal metal pins have been used at other locations [36] but they have not been considered useful for Thailand sites.

The selection of optimum methods is essential because conservation strategies are seldom reversible. For example, construction of a poorly designed shelter may result in specimen damage. Likewise, sealants, consolidants, and adhesives are seldom removable. Installation of bands or pins requires drilling into the fossil. Conservation of fossil wood is therefore not a trial-and-error process, but must be subject to careful testing before implementation.

Design of conservation strategies requires several types of information. Mineralogy provides evidence for understanding weathering properties of fossil wood. Environmental analysis involves issues such as climate and hydrology. The effectiveness of adhesives, sealants, and consolidants can be evaluated by laboratory analysis of test specimens. Physical testing shows that individual fossil logs may have compositional variations that influence the success or failure of various conservation methods. At Tak, porosities of fossil wood vary from 3.47% to 15.33%.Compressive strengths have a wide range of values, partly because of compositional variations but also because of grain orientation. Cross-sections have 1.5–3 times higher resistance to pressure than longitudinal sections (Figure 21).

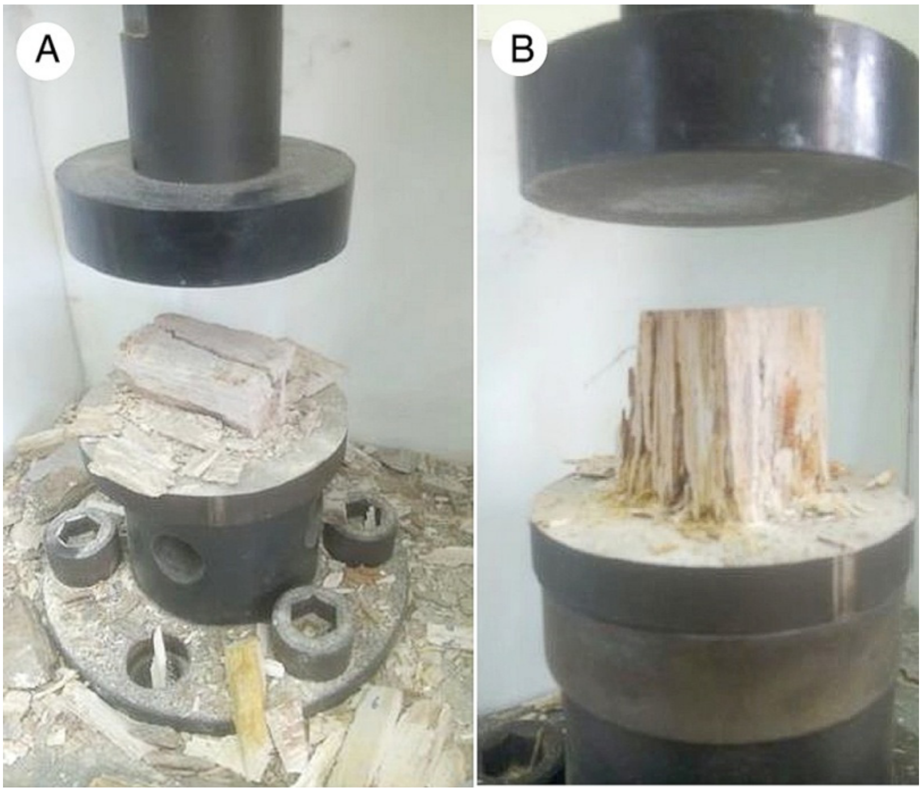

Figure 21. Testing compression strength. (**A**) longitudinal orientation. (**B**) transverse orientation.

Conservation treatments of the petrified wood at the two sites, especially Tak, pose technical problems. One is the severity of the climate. Attempted conservation methods fall into two categories: physical and chemical. Physical methods include shelter and roof renovation to maintain the stability of temperature and humidity or minimize the fluctuation of environmental change, drainage system improvement, and ground leveling to prevent the soil from sliding to fossils. Chemical methods include cleaning, repairing the broken part, filling the missing part, and strengthening fossils with consolidants. However, the most important consideration is environmental control. Chemical methods are costly and should be avoided to use unless necessary and should be considered only after environmental fluctuations have been minimized.

7. Conservation Methods: Tak Locality

7.1. Protective Shelters

After the 2003 excavations, temporary shelters were constructed to protect some logs from direct rain and sunlight (Figure 22). Roofs supported by bamboo frame and ironwood (*Xyliaxylocarpa*) poles were made from local plants such as cogon grass or leaves of *Dipterocarpus tuberculatus* trees, gathered by members of local ethnic groups. Final assembly was a cooperative effort directed by park staff. A permanent shelter was constructed for trunk BT-1 in 2011. More permanent shelters were installed in 2016–2017 to protect fossil trunks BT-6 and BT-7. BT-2 to BT-5 either have a temporary shelter or no shelter because of limited resources.

Despite their many advantages, the shelters have limitations and weathering processes still continue. The temporary shelters do not provide an adequate dry zone during monsoon because the too-narrow roofs allow wind-blown water to enter the pits that contain fossil logs. The useful lifespans of these shelters is only a few years because of weathering, with summer temperatures of >40 °C and heavy rains during the 4month monsoon; termites create gaps or holes. Permanent shelters also have imperfections. For example, log BT-1 is sheltered under a roof constructed of translucent polyester panels alternating with opaque metal sheets (Figure 23). The upper end of the trunk receives strong sunlight in the morning.

All Tak petrified logs in shelters are positioned under roofs that are properly designed to provide complete protection from sunlight. An example of biogenic degradation is the deposition of fecal material from birds nesting beneath the shelter roof, providing a source of chemical contamination [41].

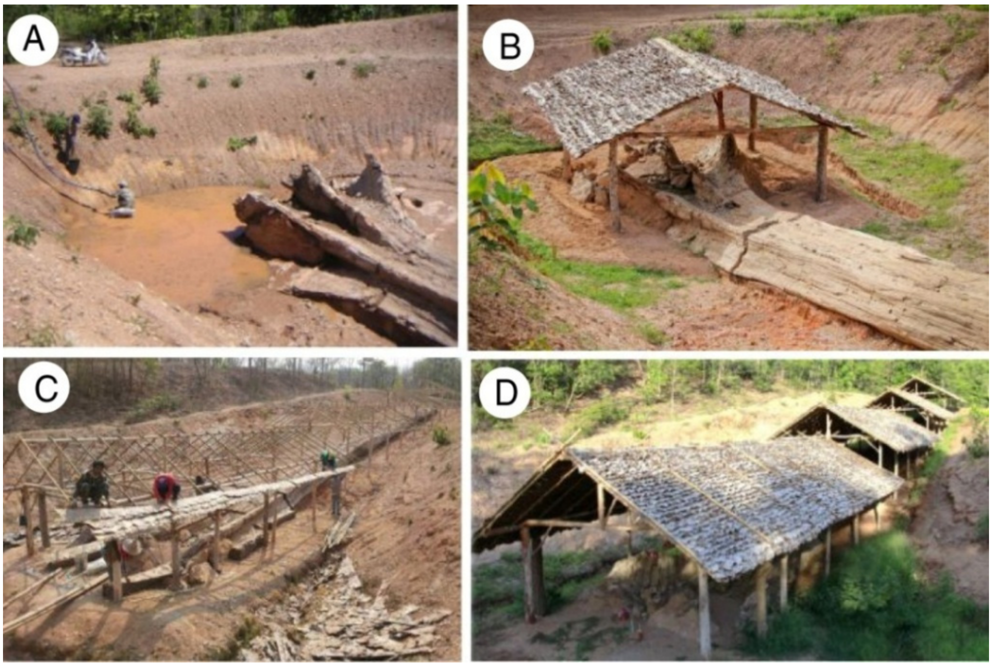

Figure 22. Early conservation at Tak. (**A**) Log BT-7 flooded at the buttress in 2006. Photo from the national park staff. (**B**) BT-7 temporary shelter and drainage in 2013. Photo by Nakaporn Limrachtamorn. (**C**) Construction of a temporary shelter by park staff and the locals. (**D**) Completed temporary shelter.

Damage from sunlight exposure is associated with the presence of moisture, hygroscopic secondary minerals, and soluble salts.Clays and iron oxides in void spaces expand and contract in relation to changes in moisture, resulting in physical stresses.Light exposure allows photosynthetic microbes to grow on the surface of fossils, resulting in surface discoloration.

Salt weathering is a particular concern. The conditions required for this weathering to occur are the presence of soluble salts (NaCl, Na_2SO_4, etc.), a porous host material where dissolved salts are adsorbed, and temperature or precipitation cycles that cause the salts to undergo physical transformations. It is the expansive forces of crystallization that causes weathering damage [42,43]. For dry rock, thermal changes caused by alterations of shade and sunlight are relatively benign. The sources of soluble salts could come from weathering of the sediments adjacent to the fossil trunks, but concrete used in the construction of permanent structures is a potential source [44,45]. Measurements of pH, conductivity, and salinity made on powdered samples immersed in distilled water show high levels of dissolved salts in the soil surrounding the wood, and in weathered exterior regions of the logs (Table 3).

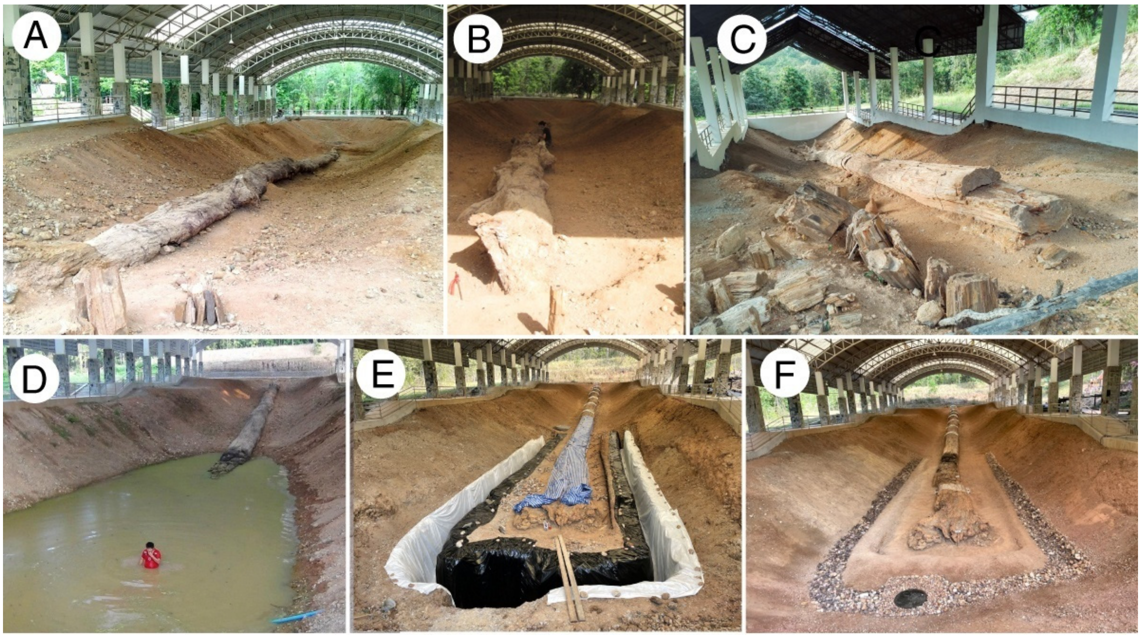

Figure 23. Imperfections and improvements of permanent shelters. (**A**) BT-1, showing discoloration from chemical application on the top and microorganisms at the middle. (**B**) BT-1 showing contrast between shade and sunlight. (**C**) The narrow roof of the BT-7 shelter allows sunlight exposure to most of the trunk in late afternoon. (**D**) Monsoon flooding of BT-1 shelter, October, 2011. (**E**) 2021 BT-1 shelter Installation of water barrier fabric: geotextile (white) and geomembrane (black). (**F**) Completed water barrier, with gravel filling. (**E**,**F**) photos courtesy of Phoobet Sakha.

Wind-blown rain still reaches the fossil, and the low topographic position of the excavated log allows water exposure (Figure 23D). The shelters BT-1 and BT-7 were inclined parallel to logs, which created three different environments: damp low elevations, a drier middle zone, and very dry upper region.

To summarize, a major theme of our interpretation is that the most important conservation issue for Thailand's fossil forests is the need for effective management of water, including avoiding direct precipitation, wind-blown rain, seasonal flooding, dampness of the sediment that supports the fossil logs, and direct exposure to sunlight.

7.2. Design Improvements for Shelters

By 2011, the buttress of fossil tree BT-7 had greatly deteriorated comparing with the 2003 discovery and the temporary shelter was rebuilt. In 2016, DMR in collaboration with the Department of Groundwater Resources re-designed permanent shelters for BT-6 and BT-7. Changes included installation of ceiling nets to prevent bird perching (Figure 24). However, the nets proved to be attractive to nesting birds. The 2019 investigation completedby a team of conservation landscape architects revealed that the main causes of deteriorationwere fromsalt weathering caused by the cement used in permanent shelter construction, and rising dampness for logs lying on the ground surface.The current permanent shelters still do not provide stable environmental control because fossil logs rest on seasonally damp ground and are intermittently exposed to direct sunlight. The proposed action calls for renovation of three large permanent buildings and construction of four new structures to provide improved environmental controls [46], but because of the high cost, the plan has not yet been implemented.

Table 3. Measurements of pH, conductivity, and salinity for Tak samples.

Sample	pH	Conductivity (µS)	Salinity (ppm)
Unweathered wood			
BT-1	6	91	60
BT-1	6	174	86
BT-1	6	121	80
BT-2	5	80	40
BT-3	5	75	35
BT-4	5	34	16
BT-5	5	35	20
BT-6	5	70	34
BT-7	5	50	29
Mean	5.3	81	44
Weathered wood			
BT-1	5	164	110
BT-1	5	199	101
Soil			
Near BT-1	5	304	153
Near BT-1	5	358	148
Near BT-1	5	112	50
Near BT-4	5	322	162
Mean	5	274	128

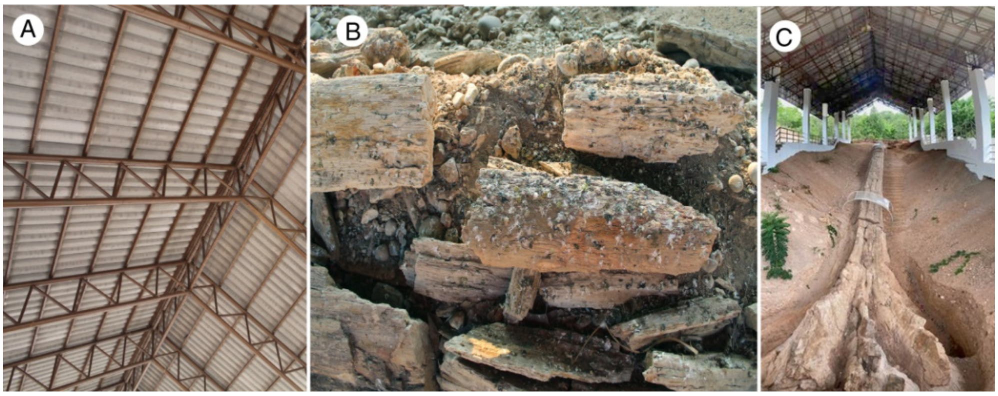

Figure 24. Permanent shelter roofs attracted nesting birds, whose droppings contaminated fossil logs. (**A**) Original roof of shelter BT-6. (**B**) Fossil wood showing abundance of fecal material. (**C**) Ceiling screen installed to prevent bird entry. A small temporary canopy positioned above the middle of the trunk provided local protection against bird excrement. Photo by Tanaklit Teja.

In 2021, the Ministry of Natural Resources and Environment in collaboration with the organization under its administration submitted an application to the Guinness Bookof World Records for the BT-1 log being as the world's longest silicified fossil tree trunk. This entry was certified on 11 May 2022, followed by an award ceremony on 8 July 2022. The DMR and the national park in collaboration with the Engineering Institute of Thailand (EIT) and Kasetsart University have improved the drainage system at the buttress area of BT-1 to prevent flooding using Geotextile and Geomembrane. However, the fossil is still partially buried in the ground, which allows moisture permeation. Thus, long term observing and monitoring will always be required.

7.3. Chemical Treatments

Chemical treatments have long been popular for architectural applications, particularly for porous sandstone used as building stone. They work less well for geologic materials that have lower permeability. Chemical treatments are unlikely to be effective for specimens that are in direct soil contact, where moisture can penetrate into the material. Surface coatings inhibit evaporation from the upper surface, and trapped water may result in an increase in weathering rates. The performance of water repellent treatments that allow passage of water vapor (e.g., organic silicates) have the potential for reducing water absorption in fossil logs, but the most effective strategy is preventative: controlling environmental conditions to prevent weathering damage rather than trying to restore fossils that have reached a state of degradation.Chemical treatments have the illusion of offering a simple cure for remediating deterioration, but these products are likely to require repeat applications, and results may be uncertain. In contrast, the design and construction of protective shelters has high initial cost, but the ultimate value can outweigh repeated short-term "quick fixes".

Descriptions of experimental chemical treatments appear in Table 4.

Table 4. Performance characteristics of experimental chemical treatments used at Tak.

Product	Chemical Component	Peformance Notes
	CONSOLIDANT	
PARALOID B-67 Dow Chemical Corporation, www.dow.com (accessed20 July 2022)	Paraloid B-67 is the most hydrophobic member of the Paraloid family of thermoplastic acrylic resins. It provides excellent water resistance in addition to its value as a consolidant.	Applied on log BT-7 during 2013–2014 tests. Coating is transparent, but with a slightly glossy surface. If the mixture ratio is not suitable. Brush application produces bubbles that are related to the porosity of the specimen. Limited depth of penetration made this product unsuitable as a consolidant.
PARALOID B-72 Dow Chemical Corporation, www.dow.com (accessed 20 July 2022)	Paraloid B-72 is an acrylic resin (ethyl-methacrylate copolymer) used as a consolidant or strong adhesive. Resin comes in solid pellets which are dissolved in an organic solvent for application. Acetone was used in our experiments.	Depth of penetration was 5–10 mm, too low for the resin to be an effective consolidant. SEM image show that the coating did not completely cover the porous wood surface, allowing water penetration. The glass transition temperature of 40 °C is reduced by acetone and other solvents, falling below common summer temperatures at Tak. Paraloid B-72 is often used for surface coating or as adhesive in conservation of glass, ceramic objects, and fossils stored indoor. However, it is not suitable for fossil Tak wood
SILRES BS-100 Wacker Chemical Corporation, www.wacker.com (accessed 20 July 2022)	Silres BS OH 100 is an alcoholic solution of ethyl silicate solution that penetrates porous stone. Reaction with water from atmospheric humidity or the moisture in the capillary pores causes a glass-like silica gel binder (SiO_2.aq.) to form. The product does not contain any hydrophobic additives such as silanes or siloxanes, so it is a consolidant but not a water repellent.	This product was reasonably effective as a consolidant. A potential problem is the possible presence of soluble salts, which can reduce the effectiveness of ethyl silicate solutions. A positive attribute is that when they are applied properly, ethyl silicate consolidants are invisible on the specimen surface. A drawback is high cost.
Lime water	Aqueous calcium hydroxide solution	Application is by repeated spraying (up to 40 times for architectural applications). Lime water penetrates into porous stone to produce a strengthened layer. This zone remains permeable to water vapor, allowing trapped moisture to escape. Lime was most effective for fossil wood samples that had relatively low porosity interconnecting pores. Less protection was observed for samples with high porosity and large-diameter pores. The surface appearance of treated specimens was only slightly altered.

Table 4. *Cont.*

Product	Chemical Component	Peformance Notes
	WATER REPELLENT	
RHOXIMAT RC-80 with HD224 RhodiaChimie (BolognepBillancourt Cedex, France	Ethyl silicate and poly-methyl-siloxane in alcohol solvent. Diluted 1:1 for application.	This product performed very well for reduction in water absorption (99.5%), while maintaining 86–88% permeability to water vapor.
SILRES BS SMK 1311 Wacker Chemical Corporation, www.wacker.com (accessed 20 July 2022)	This product is a microemulsion concentrate containing silanes and siloxanes. It is diluted with water for application. Silanes and siloxanes are susceptible to hydrolysis that occurs only after application to the substrate. The emulsion is converted into a silicone resin water repellent.	Silicone microemulsions were found to be the most efficient of the products tested, providing a high degree of water repellency. Visual observations revealed that treated samples did not change color. SEM images confirmed that the tested water repellents did not block the pores of the petrified wood. For both Silres products, the water absorption of treated test pieces is considerably lower than for untreated test pieces. A disadvantage of these products is high cost.
SILRES BS 4004 Wacker Chemical Corporation, www.wacker.com (accessed 20 July 2022)	This emulsion contains a stabilized mixture of silanes and siloxanes.	
	RESTORATION FILLER	
Lime mixed by hand with water and sand to make a viscous paste	Mixture 1: Slaked lime and coarse sands mixed in a volume ratio of 1: 3 Mixture 2: Slaked lime and fine sand mixed in a volume ratio of 1: 3 Mixture 3: Slaked lime and fine sand mixed in a volume ratio of 1:4 Mixture 4: Slaked lime and mixed size fine sand with a lime/sand volume ratio of 1:3	Mixing of lime, sand, and water produce an inexpensive material for filling fractures and open spaces on fossil logs. The mixtures can be tinted with iron oxides, brick powder or other inorganic pigments to provide an approximate color match (Figure 25). The physical properties of sand affect the plasticity of the paste and the hardness of the final material. Fine sand increases adhesion and workability, but the lime/sand mix has greater shrinkage during curing and lower ultimate strength. Conversely, lime mixed with medium and coarse sands have lower shrinkage, but with a reduction in workability. In all cases, the sand should be clean with irregular grain shapes (e.g., angular rather than well-rounded). Poorly-sorted sands (mixed sands) produce intermediate results between fine and coarse sand mixtures, and they may be a useful alternative. Mixed sand gives better strength than coarse sand. However, coarse sand and mixed sand in the mixtures decreases the water absorption of the hardened mixtures. Mixtures of lime and coarse sand can be used to fill large cavities. Smaller flaws can be filled using lime with fine or medium sand. Lime/coarse sand mixtures have greater compressive strength than lime/fine sand mixtures. Vapor permeability is related to the porosity and median pore diameter (MPD) and median pore volume (MPV) of the hardened lime/sand mix. Mercury porosity measurements were used to provide quantitative evaluations. For example, 1:3 lime/coarse sand had a MPD of 1×10^{-17} m compared to 9×10^{-18} m for 1:3 lime/fine sand. The MPV for the line/coarse sand mixture was 6.34×10^{-16} m^2, and 2.893×10^{-10} m^2 for the fine sand/lime mix. These data show that although the lime/fine sand mix has smaller pore diameter, the overall porosity is greater than for the line/coarse sand paste.

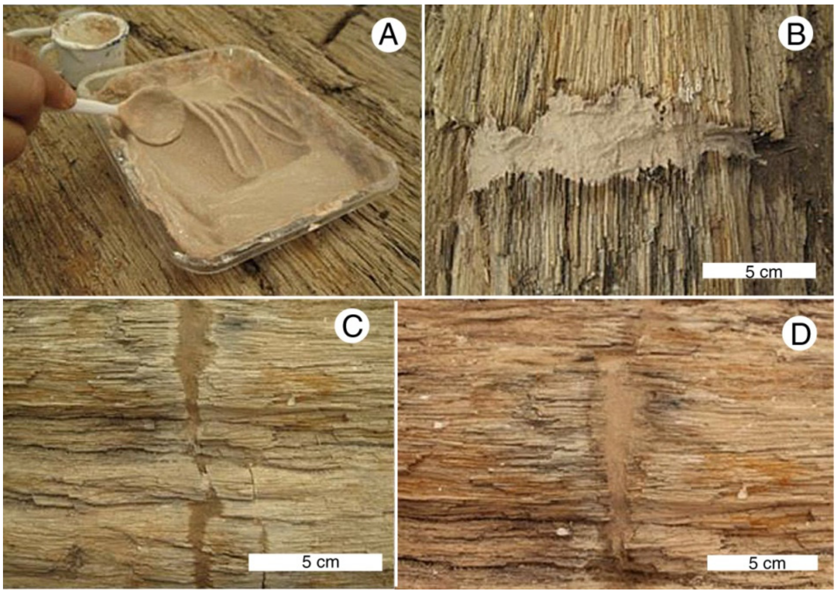

Figure 25. Lime/sand paste tests. (**A**) Mixing lime and sand. (**B**–**D**) Lime paste used to fill open fractures in Tak fossil wood. Natural or commercial pigments can be used to tint the mixture to provide an approximate color match.

7.4. Overview of Experimental Chemical Treatments

Continuous monitoring of water absorption and rising dampness on the petrified wood after the improvement of shelters and drainage systems can provide valuable data for the decision making. If the results show that moisture exposure is not a severe threat, water repellents may not be needed. However, this treatment may potentially offer protection to vulnerable areas. To be effective, consolidants must penetrate deeply into porous stone to increase durability.

Various organic resins are sold for stone conservation, but organic silicates (silicones) are in wide use. Ethyl silicate and other organic silicates have several potential advantages. After curing, these materials coat the surfaces of individual mineral grains with a film of silica, leaving pore spaces open to allow escape of water vapor. The curing process produces SiO_2 as the final product, similar in composition to the silicified wood. Color and texture of the specimen are likely to be only slightly affected, in contrast to the glossy surfaces that may result from acrylic resins. Despite their positive attributes, organic silicates have some drawbacks. They are relatively expensive, and not removable, and theireffectiveness depends on depth of penetration. They can be highly effective for porous stones, but less useful for other geologic materials. If the penetration is not deep enough, the near-surface area that the chemical penetrates will become harder than the interior and later cause splitting.

For all of these products, the challenges are formidable. Thermoplastic resins (e.g., Formvar, Butvar) dissolved in organic solvents have long been used for conservation purposes [47,48]. The most popular consolidant for paleontology is Paraloid B-72, a methacrylate polymer that inhibits water absorption of the samples owing to the development of a plastic surface film and filling of pore spaces. However, tests for Tak samples revealed that surface protection is imperfect (Figure 26). With extended contact water penetrates the treated samples. Tropical climate also poses problems. Application of consolidants to petrified wood requires appropriate temperature control. Paraloid B-72 has a glass transition temperature of 39 °C [49], but atmospheric temperatures at Tak petrified wood sites commonly exceed 40 °C in March–mid May. Although Paraloid B-67 has a higher glass transition temperature than B-72, it is still less than the temperature of some exposed fossils in summer and can cause discoloration. Also, these thermoplastics resins can only be applied to dry specimens. The greatest problem is likely to be the penetration of moisture within logs that are in contact with damp ground, where the trapped water eventually causes the surface coating to peel.

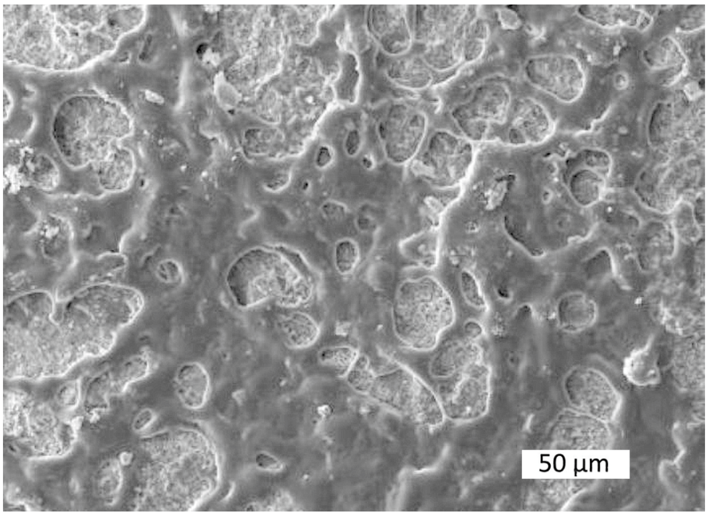

Figure 26. SEM micrograph of the samples taken from Tak petrified wood after the application of 10% solution of Paraloid B-72 in acetone. Note the incomplete surface coverage.

Lime paste is relatively inexpensive compared to synthetic resin fillers (e.g., epoxy) and although initial results are cosmetically promising, use of lime mortar for architectural purposes has resulted in many reports of deterioration during outdoor exposure [50–52]. Long-term performance at Tak remains to be determined.

All of the experiments with these chemical agents have been based on a very limited basis involving a small number of samples with observation times of 10 years or less. Long-term performance of the products needs to be evaluated. New products should also be tested.

7.5. Administrative Actions

A current strategy is to upgrade the protection status to produce a single national park by combining two other protected areas in Ban Tak District, NamtokHuai Mae Kai Forest Park and Kaeng Huai Tak Forest. In May 2018, the name "the Petrified Wood National Park" was changed to "Doi Soi Malai National Park" because the protected area covers Doi Soi Malai, a mountainous area in Mae Tuen Wildlife Sanctuary. The proposed new park has been renamed to "Doi So iMalai—Mai Klai Pen Hin National Park. In Thai *Mai Klai Pen Hin* means "wood become stone", a.k.a. petrified wood.

Another approach is a proposed Mai Klai Pen Hin Geopark under the provisions of the UNESCO Global Geopark model for sustainable development. UNESCO Global Geoparks are single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education and sustainable development [53]. The proposed geopark covers four districts in Tak. The long history of cooperation between agencies, research scientists, and the generalpublic make the site eminently qualified for UNESCO geopark status [54].

8. Conservation Strategies: Khorat Locality

Khorat or Nakhon Ratchasima Province, northeastern Thailand, has the evidence of Thailand's first fossil conservation efforts. These began in 1921, when King Rama VI visited the railway bridge crossing the Mun River at Ban TakutKhon. The chief engineer presented the King with a petrified log found in the riverbed as a goodwill gift. The King suggested conserving the log in the local area, and it remains on display as a monument at the bridge.

Several factors make Khorat fossil woods less susceptible to weathering damage than the logs at Tak Petrified Forest. The more complete mineralization reduces vulnerability, increasing mechanical strength and limiting the accumulation of weathering products in spaces within the preserved tissue. The reduced permeability also hinders biologic activity. The Khorat Plateau has low seismicity [55], so buried logs are less likely to be fractured from tectonic forces.

Some Khorat fossil logs remain partially buried, including specimens that have been partially excavated as displays. However, the Museum of Petrified Wood and Mineral Resources in Nakhon Ratchasima has many fossil wood specimens that are displayed as indoor exhibits, as well as logs that are located outdoors in an attractive garden setting. The museum has been an important resource for protecting Thailand's fossil treasures from exploitation by private collectors and commercial fossil dealers. Thailand, similarly toalmost all countries, lacks a sufficient number of paleontologists to adequately study fossil discoveries, and the establishment of the museum is a notable achievement.

After a decade, some fossil logs displayed in the garden were observed to have developed darkened surfaces caused by microbial growth (Figure 27). Fossils located within outdoor shelters were vulnerable to damage because of flooding during the rainy season. In 2016, the longest trunk was excavated and mounted on an above-ground pedestal next to the path (Figure 28). A replica replaced the original log.

Figure 27. Fossil logs at Khorat petrified wood museum show dark discolorations from microbes.

Figure 28. Conservation efforts at Khorat in 2016. (**A**) Workers prepare a mold for a log in wet ground so that a replica can be made. (**B**) Removal of the log so that it can be displayed on a pedestal. (**C**) Completed exhibit, with fossil log on a concrete pedestal and replica in excavation pit.

Indoor displays at the museum are protected from the effects of weather, but these displays are not without possible risks. For example, air conditioning can produce lower humidity compared to the natural setting. Outdoor garden exhibits have the advantage that the fossil wood is no longer in low topographic positions that are at risk of flooding during the rainy season, but problems may arise. A conservation issue for outdoor displays at the Nakhon Ratchasima museum is the precipitation of surface coatings of calcium carbonate caused by evaporation of water deposited by sprinklers used to irrigate nearby lawns (Figure 29).

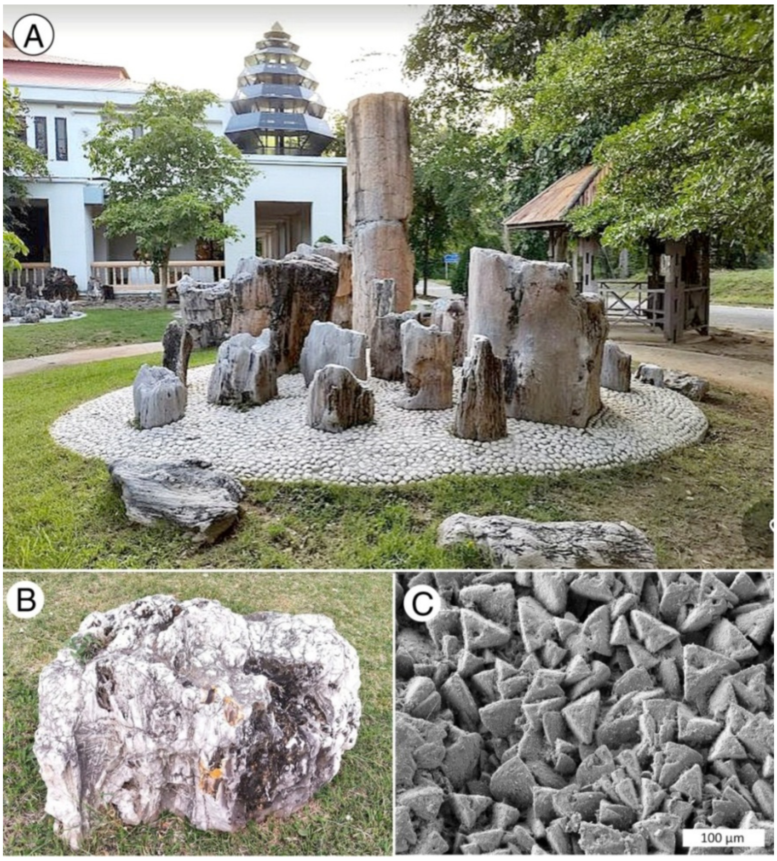

Figure 29. Outdoor displays of fossil wood at Khorat Petrified Wood Museum. (**A**) Garden plaza exhibit. (**B**) Log S-11 showing white surface crusts caused by evaporation of water used for irrigating adjacent lawn. (**C**) SEM image of calcium carbonate crust on log S-11.

The cause of these surface coatings is the hardness of the local water supply. Groundwater in the Khorat Plateau is recharged by the tropical monsoon rainfall, with an annual average of about 1330 mm [56]. The 6month dry season causes surface water to be insufficient for domestic and agricultural purposes, and aquifers accessed by wells are an important resource [57]. The hydrogeochemistry is variable depending on seasonality and geographic location, but underlying beds of limestone and gypsum contribute Ca, Mg, and sulfate to the groundwater. Well depth has an influence on water quality. Five aquifers occur in the Khorat region: alluvial, upper siltstone and shale, two sandstone formations, and nodular limestone conglomerate. All of these aquifers contain Ca as the dominant cation. Well depths below approximately 100 m may also contain high levels of Na released from subsurface salt domes [58].

The calcareous coatings that have developed on some of the logs in the museum garden are an issue that could potentially be mitigated by changes in display design or lawn watering strategies.Chemical treatment of affected specimens is a possibility, similar to the acid treatments that are used to remove calcareous mortar stains that develop on brick and building stone [59].

9. Conclusions

Petrified wood sites in Khorat and Tak are notable for their unique characteristics. These fossils are spectacular in size and abundance, and they have great scientific importance. In addition, these fossil sites generate significant revenue for local communities via geotourism. The establishment of the petrified wood museum and national park brought each site more than 100,000 visitors annually before the Covid pandemic. The fossil forest sites also have great potential for education, and programs are being developed for in-person classes and video-based instruction that allows international access.

For these goals to be successfully met, effective conservation methods are essential. The deterioration of fossils contributes to a decline in visitors, and the protective measures that have previously been attempted have been imperfect. However, they constitute an important resource for designing future improvements. One lesson is clear: effective conservation strategies depend on empirical evidence, and trial-and-error methods are unacceptable.

Our study demonstrates the importance of mineralogical analysis for understanding the weathering characteristics of fossil logs. The purpose of this research was not to produce a comprehensive analysis, but to instead provide a general overview. Our data are based on a limited number of samples that do not necessarily represent the range of compositional variations and physical qualities that may exist in large fossil trunks, but the research illustrates the kinds of evidence that can be obtained by standard analytical methods that include XRD, SEM, and thin section petrography.

Experimental procedures allow evaluation of possible values chemical treatments, and observations of past attempts at environmental controls via shelters and water management provide valuable information, but the imperfect results mean that uncertainties remain.

No final decisions can be made until more data are available. However, several factors are involved. Because of the tropical climate, protection of fossils trunks requires construction of shelters that minimize fluctuations in temperature and moisture contact. Treatments with consolidants, adhesives, and water repellents are not a substitute for effective environmental controls. These chemicals may have some future value, but it is important to remember that these materials cannot bring back the original condition of petrified wood, but they can help to delay the deterioration process. Finally, fossil conservation is a long-term process that can best be achieved by the cooperation of a spectrum of people that includes scientists, educators, government officials, and everyone who works in these parks or visits them. The ways to pursue this goal are to conduct conservation training workshops for staff and volunteers, to create a conservation plan that includes catalog records for each petrified log, and to establish site-trained staff and volunteers who are directly responsible for documentation and monitoring. Adequate budgets are necessary to achieve these goals. However, weather and climate are dynamic processes, and even well-planned conservation practices will require continued monitoring.

Author Contributions: G.M. and N.B. conceived this investigation, and wrote the first manuscript draft. N.B., P.J., C.A. participated in field investigations and provided extensive references, including translations originally published in Thai language. G.M. analyzed Tak and Khorat specimens using laboratory facilities at Western Washington University, Bellingham, WA, USA. C.A. performed conservation testing on Tak specimens using laboratory facilities at Chulalongkorn University, Bangkok, Thailand. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Original trunks are preserved and displayed on sites at the proposed Doi Soi Ma Lai—Mai Klai Pen Hin National Park, Tak province, Thailand. The fragment pieces of specimens analyzed for this project for mineral composition are archived in G.M.'s research collection at the Western Washington University Geology Department. Specimens for conservation arearchived in C.A.'s research collection in Bangkok. These materials include thin sections, SEM specimens, and numerous digital photomicrographs; all are available to other investigators upon request.

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