REVIEW OF THE FOSSIL WOODS IN VIETNAM'S TERRITORY

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Abstract

Fossil woods have been found in many localities in Vietnam's territory in geological formations of the Devonian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary periods. Originally, they were woody plants belonging to phyla Lycopodiophyta, Polypodiophyta, Gymnospermae, and Angiospermae. After death, the plants were buried under specific conditions and the organic components of the wood were replaced by minerals such as agate, opal, calcite, etc. At present, fossil woods are used for decoration in homes and offices and are exhibited in museums and parks. In this paper, we present basic information on fossil woods, their geological ages, research methods used to study them, and their scientific and artistic significance.

Keywords: Cretaceous; Devonian; Fossil woods; Jurassic; Neogene; Paleogene; Quaternary; Triassic; Vietnam.

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1. INTRODUCTION

Fossil wood is the common name given to all fossilized woody plants. Petrification is a long mineralization process under specific environmental and anaerobic conditions in which plant tissues are replaced with mainly SiO_2 and CaCO_3 minerals. Usually, the organs in the stem are replaced with minerals while maintaining the original structural system of the cell tissues.

By definition, fossil wood is a specific form of fossil of the plant kingdom. Like other fossil groups, fossil woods are subjects of paleontology related to geological formations. Besides their taxonomic significance in paleontology and use in determining geological age, fossil woods also help us learn about prehistoric environments and the evolution of the Earth's crust.

In addition to scientific significance, fossil wood today is used for many different economic and spiritual purposes such as feng shui art, ornamental stones, home guardian sculptures (pixiu), and jewelry (bracelets). Some types of petrified wood are formed solely of quartz crystals (SiO_2) in the form of opal, chalcedony, or agate, and display beautiful pure colors. They are employed by psychics as a talisman to fight dark forces, to wish for a prosperous business, and to achieve promotion on the path to fame. As fossil wood in the form of agate is considered a symbol of health, the owner of an agate fossil wood ring becomes more confident in communication (Ngoc Thach Thao Gemstone, n.d.).

Figure 1. Plant fossils in North America

Note: a) Plant fossils of the genus *Wattieza* discovered in New York State, the United States of America, in 2007; b) Plant fossils of the genus *Archeopteris* from Miguasha National Park, Quebec, Canada.

Source: Migusaha National Park (2007).

Fossil wood appears in most countries of the world and at many different stratigraphic levels. The oldest fossil wood is possibly the genus *Wattieza* found in New York State, USA, in 2007 (Figure 1a) of middle Devonian age (about 385 Ma). Previously, paleontologists had discovered the fossil tree *Archaeopteris*, a genus of Progymnospermophyta thought to be the earliest woody plants (Figure 1b) of late Devonian age (382.7 - 358.9 Ma).

Figure 2. Stratigraphic and geographic distribution of fossil wood in the territory of Vietnam

Source: “Study, collection of fossil woods in Vietnam for exhibition in the System of Vietnam National Museum of Nature” (CT0000.01/19-21).

(a)

(b)

(c)

Figure 3. a) Onyx fossilized tree at Dong Xanh Park, An Phu commune, Pleiku city, Gia Lai Province; b) Onyx fossil wood; c) Agate fossil wood bracelet

Source: Figure 2a) Authors; Figure 2b & 2c) Ngoc Thach Thao Gemstone (n.d).

Fossil wood in Vietnam appears in many stratigraphic levels of the Devonian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary (Figure 2). Only a few fossil woods were studied by French paleontologists (Boureau, 1950a, 1950b, 1952, 1958; Serra, 1966a, 1966b, 1967, 1968, 1969; Boura et al., 2013). Most of the remaining fossil wood remains unidentified though. Fossil wood today is sold in art, silver, or gem shops and displayed in family living rooms, offices, museums, and parks in all provinces and cities in the country (Figure 3).

Some fossil wood in Vietnam is associated with scientific names, such as “Stem of the elder family,” “Water pine,” or “Fossil cones” in paleontological classification. However, most fossil wood has not yet had the results of analysis and assessment of its full scientific significance. Nowadays, the study and classification of fossil wood in the territory of Vietnam in scientific terms are necessary. Adequate studies on fossil wood will help the community understand its nature and scientific significance, and, more importantly, meet the criteria for categorizing fossil wood on an anatomical basis and to judge its aesthetic, economic, and artistic values in feng shui.

2. OVERVIEW OF FOSSIL WOOD

2.1. Some general concepts about fossil wood

Mold fossils: *Mold fossils* are common for woody vascular plants. The inner woody tissue does not remain during the replacement, but the characteristics of the bark, leaf structure, or root system remain in the form of external molds that allow the identification and classification of the fossil wood. The taxonomy of rhododendron fossils is mainly based on these characteristics.

Carbomorphism: The charred wood found in coal mines from the Devonian to the Neogene usually does not preserve the wood tissue structure. However, in some cases, the coalification process is not affected by geodynamic metamorphism. The woody tissue structure remains, and like petrified wood, can be studied in thin sections under the microscope.

Petrified wood: Petrified wood is a form of fossil that has turned into stone through the process of permineralization. Minerals replace the organic material of all woody plant organs via a long mineralization process in an anaerobic environment. All organic matter is replaced by silicon oxide (SiO_2), calcium carbonate (CaCO_3), or converted to charcoal (C) under certain pressure and temperature conditions, but keeping the original structure of the wood.

Mummified wood: Mummified wood is a woody plant fossil that is not petrified. It is noteworthy that “fossil” in paleontology does not mean that all organic remains that become new rock are called fossils. The term, fossil, in paleontology implies a meaning related to the time of existence of the organism, or in other words, to geological age. In conventional paleontology, all biological remains in geological formations dating back 10,000 years or more are fossils, regardless of whether those remains are petrified or not.

Mummified wood appears when trees are rapidly buried in the cold arid climate of the northern hemisphere, in a hot desert, or in an anaerobic environment that does not have enough oxygen to decompose wood tissue. Mummified woods are of great significance in paleobotanical studies; they leave behind primitive organic cells and tissues, potentially allowing examination with technical equipment used in modern research studies of dendrology. Examples include mummified woods on Ellesmere and Axel Heiberg islands in Canada and desiccated tree trunks in the African Sahara and the Gobi desert in Central Asia, the two largest deserts in the world. In Vietnam, mummified woods are prevalent in the coal mining areas of Na Duong and Lang Son.

Submerged forest: This is a relic of a forest flooded by the sea and is of great significance in determining sea level rise between ice ages (Heyworth, 1987).

2.2. Fossil wood in the world and Vietnam

In the world: Fossil wood is found in many countries: India, Cambodia, Indonesia, Myanmar, Laos, Thailand, China, Australia, New Zealand, Argentina, Ecuador, Brazil, Canada, United States of America, Russian Federation, Belgium, Czech Republic, Federal Republic of Germany, Egypt, Greece, Italy, Libya, Madagascar, Ukraine, United Kingdom, etc., in sedimentary rocks and deposits of volcanic eruptions from 385 million years to 10,000 years BP.

Around the world, many countries have built conservation areas and parks to display and preserve the natural remnants of prehistoric times. Fossilized wooden trunks are mostly located outdoors, although some are in museums and research institutes. Petrified Forest National Park in northeast Arizona has thousands of large coniferous fossil trees. Other US sites include Ginkgo Petrified Forest State Park in Washington, Petrified Forest in California, Mississippi Petrified Forest in Mississippi, Gilboa Fossil Forest in New York, Gallatin Petrified Forest near Yellowstone National Park, Escalante Petrified Forest State Park in Utah, and Petrified Wood Park in Lemmon, South Dakota. Sarmiento Petrified Forest and Jaramillo Petrified Forest in Santa Cruz Province, Argentina, have many fossil trees over 3 m in diameter and 30 m in length. The Natural History Museum in Chemnitz, Germany, has a collection of petrified plants from the on-site Chemnitz fossil forest found in the town in 1737. Petrified Forest of Cairo-Suez Road, Egypt; the Fossil Forest in Champclauson village, France; Takapuna Fossil Forest, Auckland in New Zealand; Petrified Forest north of Riyadh, Saudi Arabia; Petrified Forest north of El-Kurru, Sudan; Xinjiang National Park in China, and Ban Tak Petrified Forest Park in Ban Tak district, Thailand are destination spots for visitors to visit and research (“Petrified wood,” n.d.).

Fossil wood in Vietnam: Research on fossil wood in Vietnam started to bloom with French paleontological studies on ancient wood tissue. A series of fossil wood samples collected in Indochina, including fossil wood collected in Neogene claystone in South Central Vietnam, was researched and published by Boureau (1950a, 1950b, 1952, 1958) in the Bulletins of the Department of Geology of Indochina and The French National Museum of Natural History and the Proceedings (Mémoires) of The French

National Museum of Natural History. In that series, the indigenous species *Terminalioxylon annamense* in the Metastomataceae family and *Sapindoxylon pleikuense* in the Sapindaceae family were established and described. In the siltstone layers of the Bach Long Vi Fm of Oligocene-Miocene age, Boureau (1958) described *Quercoxylon ogurai*, an endemic species related to the oak genera of Bach Long Vi Island. After Boureau (1958), Serra (1966a, 1966b, 1967, 1968, 1969) published new contributions to the study of Mesozoic fossil woods in Vietnam, Laos, and Cambodia. These included the description of *Phyllocladoxylon vietnamense* species of the family Phyllocladaceae, such as *Brachioxylon* sp, and *Protophyllocladoxylon thylloides* belonging to a family of plants in the phylum Gymnospermae, *Araucarioxylon* sp belonging to the family Araucariaceae in the Jurassic stratigraphy of Ho Gia, Vung Rua, and Huu Chanh areas (Quang Nam), and *Prototaxoxylon asiaticum*, *Protopodocarrpoxylon orientale*, and *P. paraorientale* of early Cretaceous age from the red sandstone exposed on Phu Quoc Island and Tho Chu archipelago, Kien Giang Province.

On the basis of silicified wood samples collected by Bui et al. (2002) during a geological investigation as part of underground water exploration drilling in Tho Chu, An Thoi, and Phu Quoc islands in the Gulf of Thailand of Kien Giang Province (Vietnam), Boura et al. (2013) studied and described three fossil wood species: *Agathoxylon colanie* belonging to the family Araucariaceae, *Protophyllocladoxylon xalucense*, belonging to the bamboo pine family (Phyllocladaceae), and *Cycadeanoxylon* sp. belonging to the family Cycadaceae. All are native species.

There were reliable results of some studies on leaf fossils by Trinh (1998) and collect spores and pollen by Nguyen, Pham and Pham of the Miocene age (See Bui, & Tran, 2005). Based on a fossil wood study using comparative anatomical methods, Boura et al. (2013) suggested that the sediments that contain silicified fossil wood on Phu Quoc Island, Tho Chu, and An Thoi archipelagos (Kien Giang) have a Late Jurassic-Early Cretaceous age.

In recent years, through the exploitation of lignite for power generation in the Na Duong coal mine, both carbonized and silicified fossil wood forests of the late Eocene-Oligocene age (40 - 23 Ma) have been revealed. Besides fossil wood, there are fossil imprints of leaves or fruit and fossils of freshwater mollusks (gastropods and bivalves), reptiles (turtles, tortoises, and crocodiles), freshwater fish, and mammals (primates, anthracotheres [Anthracotheriidae], chevon, rhinoceros). They have attracted many paleontologists from Germany, France, Thailand, Japan, and China to study (Böhme et al., 2013; Nguyễn et al., 2015). The Na Duong coal mine area is the "window" into the Eocene ecosystem of Southeast Asia. Fossil wood here has the scientific name of royal family ferns (Osmundaceae) of the class Polypodiopsida. Unfortunately, this fossil forest is still not conserved for research and tourism. Some businessmen, businesses, and agencies have come to collect samples for display, but most of the fossil wood is in the waste dumps of Na Duong Thermal Power Plant, Loc Binh district, Lang Son Province.

In the volcanic eruption area in Chu A Thai, Chu A Thai commune, Phu Thien district (Gia Lai Province), fossilized onyx wood with beautiful colors and of the highest

aesthetic and economic value has also been discovered in Vietnam. The stock of agatized wood has now been exhausted, but the scientific name of this fossil wood is still unknown in the paleontological classification system.

The known stratigraphic levels containing fossil wood in Vietnam are as follows:

- Givetian level, Devonian period (387.7 - 382.7 Ma): Fossils of Lycopodiophyta.
- Norian-Rhaetian, Triassic (228 - 201.3 Ma): Fossils of Polypodiophyta, Gymnospermae, and Angiospermae.
- Toarcian-Callovian stages, Jurassic period (182.7 - 174.1 Ma): Fossils of Polypodiophyta, Gymnospermae, and Angiospermae.
- Lower Cretaceous system (145.0 - 100.5 Ma): Fossils of Polypodiophyta, Gymnospermae, and Angiospermae.
- Paleogene and Neogene systems (66.0 - 2.588 Ma): Fossils of Polypodiophyta, Gymnospermae, and Angiospermae.
- Pleistocene Quaternary (2.588 - 0.0117 Ma): Fossils of Gymnospermae and Angiospermae.

3. CHARACTERISTICS OF THE STRATIGRAPHY CONTAINING FOSSIL WOOD IN VIETNAM AND SOME METHODS OF RESEARCH AND IDENTIFICATION

3.1. The stratigraphy containing fossil wood in Vietnam

Devonian strata: Fossils of woody plants belonging to the Lycopodiophyta branch appear in the Do Son Fm (D₂gv-D₃fr *ds*) (Figure 4), Van Huong ward, Do Son peninsula, Hai Phong city; Ban Sen commune, Tra Ban Island, Quan Lan commune, Quan Lan Island, Van Don district, Quang Ninh Province; the Tan Lap Fm (D₂gv-D₃fr *tl*) in Tam Hoa lake area, Mo Nhai lake, Hung Vu commune, Bac Son district, Lang Son Province; the Dong Tho Fm (D₂gv-D₃fr *dt*) in Hoi Da area, Quang Tien commune, Quang Trach district; and Lang Sung slope, Hong Hoa commune, Minh Hoa district, Quang Binh Province. The fossils are representatives of the genera *Lepidodendropsis* and *Protolpidodendron*. In the territory of Vietnam, fossils of plants belonging to the order Lepidodendrales of the Lycopodiophyta branch are often found in coarse-grained quartz sandstone and quartzite. The woody tissue structure in the stem is entirely replaced by quartz grains. The outer stem structure of Lepidodendrales plants usually preserves leaf scars. Based on the structural features of the petiole, paleontologists have proposed genus and species classification criteria for Lepidodendrales plants. The Lepidodendrales first appeared in the middle Devonian, then flourished in the Carboniferous period in tropical forests. They can reach 30 meters in height and 1 meter in diameter.

Figure 4. Reconstruction of *Lepidodendron* and fossil wood discovered in Do Son, Hai Phong

Note: a) *Lepidodendron* - (Reconstruction); b) Fossil of *Lepidodendropsis* from the Van Huong Fm (D₂gvvh).

Source: Figure 4a) Kritsky (n.d.); Figure 4b) Nguyễn et al. (2015).

Figure 5. Triassic carbonized fossil wood of the Van Lang Fm (T₃n-r vl), Bo Ha coal mine (Bac Giang)

Note: a) Sample CS 378/1; b) Sample CS 378/2.

Source: “Study, collection of fossil woods in Vietnam for exhibition in the System of Vietnam National Museum of Nature” (CT0000.01/19-21).

Triassic strata Triassic vegetation is very abundant in the Hon Gai Fm (T₃n-r hg), Quang Ninh Province, the Van Lang Fm (T₃n-r vl), Bo Ha coal mine area, Yen The district, Bac Giang Province (Figure 5a,b); Phan Me mine area, Phu Luong district, Thai Nguyen Province; the Suoi Bang Fm (T₃n-r sb) in Suoi Bang areas, Van Ho district, Son La Province; Me town, Gia Vien district, Dam Dun coal mine, Nho Quan district, Ninh Binh Province; the Dong Do Fm (T₃n-r dd), Pu Sang area, Ky Son district, Nghe An Province; Dong Do coal mine, Huong Khe district, Ha Tinh Province; and the Nong Son Fm (T₃n-r ns), Nong Son coal mine area, Nong Son district, Quang Nam Province. However, the Triassic flora often preserves mainly leaf imprints, while the woody parts

are mostly changed to high-grade anthracite without preserving the wood tissue structure. Classification of Triassic flora in Vietnam is not based on wood tissue structure but mainly on the morphology of leaf imprints. Today, some carbonized woody trunks of the Triassic flora have been found in Bo Ha coal mine, Bac Giang Province, but the samples are imperfect and do not preserve the wood grain structure.

Jurassic strata: Preservation of both leaf imprints and fossils of tree trunks is a common feature of the Jurassic flora in the territory of Vietnam. Fossil wood occurs in the Ha Coi Fm ($J_{1-2} hc$) in Hai Tien commune, Mong Cai city, Quang Ninh Province; in the Huu Chanh Fm ($J_2 hc$) at Khe Ren estuary, near Huu Chanh village, Dai Loc district, Quang Nam Province; in the Binh Son Fm ($J_{1-2} bs$) at Binh Son railway station, Quang Ngai Province; in the Ea Sup Fm ($J_2 es$), at Ea Sup Village, Ea Sup District, Dak Lak Province (Figure 6); at Mang Den village, Kon Ray district-Kon Plong, Kon Tum Province; and Dray Linh hydropower reservoir area, Cu Jut district, Dak Nong Province. Most of the fossil wood in the Jurassic strata is silicified and quite large, with a diameter of 0.3-1.5 m and well-preserved growth rings. Fossil wood in the Huu Chanh Fm identified by Serra (1966a, 1967) includes *Phyllocladoxylon vietnamense*, *Brachioxylon* sp., *Protophylocladoxylon thylloides*, and *Araucarioxylon* sp.

Figure 6. Fossil wood from the Ea Sup Fm ($J_2 es$), Dak Lak Province, at the Vietnam National Museum of Nature

Source: Authors.

Cretaceous strata: Early Cretaceous fossil wood discovered on Phu Quoc Island (Figure 7), An Thoi archipelago, Tho Chu archipelago, Kien Giang Province in the sandstone of the Phu Quoc Fm ($K_1 pq$), identified and described by Serra (1969), includes *Protodocarpoxyylon orientale*, and *Protophylocladoxylon xenoxylodes* of Early Cretaceous age. The most recent study by Boura et al. (2013) on the basis of the fossil wood collection of Bui and Tran (2003b, pp. 5-54) from the Tho Chu archipelago has identified *Agathoxylon colanie* (by Serra) of the (Araucariaceae), *Protophylocladoxylon xalucense* (by Boura) of the Podocarpaceae, and Cycadeanoxylon of the Gymnospermae of Late Jurassic-Early Cretaceous age.

(a)

(b)

Figure 7. Early Cretaceous fossil wood of the Phu Quoc Fm (K_1pq)

Note: a) Photograph shot in the field; b) Photograph taken at the Origin Museum in Phu Quoc Island.

Source: Authors.

Paleogene and Neogene strata: There are 43 stratigraphic units containing Paleogene-Neogene flora in the territory of Vietnam. In the Northeast of Vietnam are the Cao Bang Fm (E_2cb) in Cao Bang Province, the Na Duong Fm (E_3nd) (Figure 8a) and the Rin Chua Fm (N_1rc) in Lang Son Province, and the Dong Ho Fm (E_3dh) and the Tieu Giao Fm (N_1tg) in Quang Ninh Province. Along the Red River are the Van Yen Fm (E_2vy), Co Phuc Fm (E_3cp), and Au Lau Fm (N_1al) in Lao Cai, Yen Bai, Tuyen Quang, and Phu Tho provinces. In Ha Noi depression are Phu Tien Fm (E_2pt), Dinh Cao Fm (E_3dc), Phong Chau Fm (N_1^1pc), Phù Cừ Fm (N_1^2phc), and Tien Hung Fm (N_1^3th) (deep borehole facilities) in the provinces of Hung Yen, Thai Binh, and Hai Phong city. Along the Da river in the Northwest region of Vietnam are the Pu Tra Fm (E_2pt), the Nam Un Fm (E_3nu), and the Hang Mon Fm (E_3-N_1hm) in Son La Province. In Muong Te district, Lai Chau Province is the Nam Bay Fm (E_3nb). In the North Central region of Vietnam are the Nam Ngan Fm (N_2nn) in Thanh Hoa Province, Khe Bo Fm (E_3-N_1kb), in Nghe An Province, Dong Hoi Fm (N_1^3dh) in Quang Binh Province, Thach Han Fm (N_2th) in Quang Tri Province. Across the South Central Coast and the Central Highlands of Vietnam are the Song Ba Fm (E_2sb) and the Kon Tum Fm (Nkt) in Gia Lai Province, Di Linh Fm (E_3-N_1dl) in Lam Dong Province, Song Luy Fm (N_2sl) in Binh Thuan Province. In the Southeast are Binh Trung Fm (N_1^3bt), Nha Be Fm (N_2^1nb) (borehole facilities) in Ho Chi Minh City, and Ba Mieu Fm (N_2^2bm) in Dong Nai Province. In the Southwest is Phung Hiep Fm ($N_{13}ph$) in Hau Giang Province. In the Southwest region are HT Ben Tre Fm (N_1^2bt), Ben Tre Province; Phung Hiep Fm (N_1^3ph) in Hau Giang Province; Can Tho Fm (N_2^1ct), Can Tho city; and Nam Can Fm (N_2^2nc) in Ca Mau Province (borehole facilities). The continental shelf of Vietnam has the Ca Coi Fm (E_2cc) and the Bach Long Vi Fm (E_3-N_1bv) (Figure 8b). Most of these formations contain plant relics and lignite seams. Fossil wood in the form of carbonization, silicification, and brown carbonification occurs in the Na Duong, Bach Long Vi, and Khe Bo formations. Exploratory drilling has not yet reached the petrified trunks in the lignite seams in the formations of Paleogene, Neogene deep in the ground.

Figure 8. Oligocene and Oligocene-Miocene fossil wood

Note: a) Oligocene fossil wood, Na Duong coal mine; b) Partly carbonized Oligocene-Miocene fossil wood on Bach Long Vi Island.

Source: Authors.

Pliocene-Pleistocene strata: During the geological time from the Pliocene epoch of the Neogene period to the Pleistocene epoch of the Quaternary period (from 5.333 - 0.0117 Ma), a series of volcanic eruptions occurred in the central provinces of Vietnam in general and the Central Highlands in particular. On the Pleiku plateau (Gia Lai and Kon Tum provinces), 9 phases of basalt eruption are confirmed, covering an area of 7,000 square kilometers with a total thickness of 500 m. In the Chu A Thai mountain area, Phu Thien district, Gia Lai Province, an agatized forest has been discovered in the largest crater in Vietnam. The Chu A Thai site has become famous among hunters of precious fossil wood. The absolute ages of the Chu A Thai volcanic basalt and surrounding areas on the Pleiku plateau analyzed by K/Ar and Ar/Ar methods are 1.59 - 1.75 Ma, 2.1 - 2.6 Ma, 3.4 - 3.5 Ma, 3.9 - 4.8 Ma, 5.3 - 6.4 Ma and 6.8 - 7.4 Ma. In terms of stratigraphy, the basalts interspersed with sandstone on the Pleiku Plateau are classified in the Tuc Trung Fm (N_2-Q_1 *tt*). Unfortunately, this agatized forest is poorly preserved, and illegal logging is still widespread by local people today.

Figure 9. Fossil wood found in Gia Lai

Note: a) Agate fossil wood from the Tuc Trung Fm (N_2-Q_1 *tt*), Chu A Thai commune, Phu Thien district; b) Chu A Thai crater containing agate fossil wood.

Source: Authors.

3.2. Fossil wood research and identification methods

Field research methods: Field research combines methods applied in geological research in general and paleontological stratigraphy in particular. Methods include measuring geological cross-sections, determining stratigraphic levels containing fossil wood, and taking fossil samples. Collecting a large sample of fossil wood requires a sledgehammer and crowbar. For larger samples of 1 meter and 30 centimeters or more, a crane must be used.

Laboratory research methods: Unlike other plant fossils groups, fossil wood has its own research methods and is classified according to artificial systems. Classification of fossil wood is mainly based on the comparative anatomical method of wood tissue structure (IAWA Committee, 1989). Fossil wood may be the only part of a conserved tree when the rest of the tree is still unknown, so paleontologists use the terminology of its botanical name to identify a specific fossil wood. The term consists of the suffix -“xylon” (wood tissue) combined with the Latin name in modern botanical taxonomy. For example, *Araucarioxylon* is the woody tissue of a genus of the Araucaria family, *Palmaoxylon* is the woody tissue of a genus of the Palm family, and *Castanoxylon* the woody tissue of a genus of the Castanopsis family. Research on fossil wood follows the following procedure: (a) identification of fossil wood according to the wood tissue classification system, (b) determination of wood tissue structure corresponding to a certain plant taxonomy in nature, (c) determination of geological age, (d) determination of fossilization conditions, (e) determination of the ancient environment, and (f) determination of commercial value.

Anatomical method of oriented slicing: Oriented slicing is performed to study the wood tissue structure (Li et al., 2015; Wang et al., 2015; Srivastava et al., 2014). The trunk is anatomized in three main directions: (a) in the vertical direction, parallel to the structure of the woody tissue, (b) perpendicular to the vertical direction, or through the structure of the wood tissue horizontally, and (c) tangential to the growth ring of the woody structure. The processing of thin sections is carried out as in petrographic and paleontological research. The thin section size can be 2 x 5 cm or 5 x 10 cm.

Morphological comparison method: This is the most common method of fossil wood assessment, requiring researchers to have a comprehensive knowledge of the wood tissue structure, including ancient and modern wood tissue. Sufficient equipment and documents exist to analyze fossil wood species throughout the world and in Vietnam as well. Thin sections are analyzed and imaged under an optical microscope or a scanning electron microscope (SEM). The results are compared with published documents to determine paleontological classification, age, and formation environment.

Polishing method: This method aims (a) to determine the number of growth rings or maturity of the tree (Gregory-Wodzicki, 2001), and (b) to determine the aesthetic and economic value. The fossil wood is cut with a diamond blade saw and then ground and polished with a specialized grinding machine using chromium oxide powder, aluminum oxide powder, or diamond paste. The cross-section of the trunk is ground and polished to

calculate the maturity of the tree from the number of growth rings. This method applies to both silicified and carbonized fossil wood.

Fossil wood processing tools and facilities: Depending on the type of fossil wood and the purpose of analysis, the following tools can be used: (a) model QSQ 220-3000 mm super large stone cutter; (b) thin slicer model QG-15; (c) model MPS-250E petrographic thin slicer; (d) Kawasaki KPT-435 hand-held polisher.

Fossil wood analysis tools: Analyzing the structure and taking photographs of fossil wood tissues can be done at magnifications from 4 to 100 X using a computer-connected optical microscope. Optical microscopes are the most important means of helping assessors to classify wood tissues and to compare them with the analysis results of wood tissue in nature, thereby making conclusions about fossil wood that need analyzing. This tool is universal in geological laboratories around the world as well as in Vietnam.

Photography with a scanning electron microscope: This is a modern method commonly used in the study of paleontological samples today. Scanning electron microscopy helps resolve the three-dimensional structure of the wood tissue in the most effective way. This tool is currently in use in geological laboratories worldwide. Today, at the Vietnam Museum of Nature, researchers use a SEM in biological and paleontological research.

Application of absolute dating methods: Among the fossil wood collected in the territory of Vietnam are some types of fossil wood formed in the volcanic rock environment of Chu A Thai mountain area, Phu Thien district, Gia Lai Province. Organic wood tissue has been totally replaced by volcanic materials, including some rare elements such as Pb, He, Sr, Rb, and Ar. It is possible to apply isotopic dating methods, such as the U-Pb, He, Sr-Rb, K-Ar, and Ar-Ar methods to date fossil wood from Gia Lai Province.

4. CLASSIFICATION OF FOSSIL WOOD

4.1. Classification of fossil wood according to paleontological criteria

Classification of plant fossils is a very complex and challenging task for researchers. Paleobotanical classification is mainly based on the morphological features of the leaves or spores and pollen, which is an artificial system of classification. Traditionally, however, plant fossils are described according to the natural system of classification. Today, paleontologists are heading towards a synchronous study, including leaves, stems, roots, spores and pollen, flowers, and fruits approaching the cladistic classification system. When classifying fossil wood, paleontologists rely on the structural features of wood tissue (xylon) to determine a specific taxonomic classification according to similarities in wood tissue structure. Therefore, the fossil wood tissue classification system does not reflect genetic relationships but only reflects one aspect of the wood cell structure of the trunk. Paleontologists often associate two terms, the scientific name of a plant taxon in the natural taxonomy and the suffix "xylon" (wood tissue).

In studying fossils on Bach Long Vi Island, Boureau (1958) established the species *Quercoxylon ogurai* (plants share the same woody tissue as the genus *Quercus*). However, such nomenclature has not gained universal recognition in the world of paleontology. Located across Asia, Europe, and North America are about 80 species of plants with woody tissue structures of the genus *Quercus*-type. Many woody tissue fossils of this genus have been discovered in Tertiary and Quaternary sediments. Paleontologists also use the suffix -“inium” in conjunction with the generic name of fossil plants such as Quercinium. Different views in the paleobotanical taxonomy are still subject to debate. Some researchers used “Quercoxylon” independently to classify a series of the *Quercus* genus fossil wood and label the fossil wood of the plant genera on Earth as well. Furthermore, Serra (1966a) described some plants with homologous wood in Southern Vietnam and Cambodia. She also published a series of Paleozoic and Mesozoic woody plants in the territory of Vietnam, Laos, and Cambodia (Serra, 1966a, 1966b, 1967, 1968, 1969).

Classification systems for fossil wood usually start at family and genus levels. Depending on the data, it is possible to classify up to species and subspecies levels according to the fossil wood taxonomy. In a study of fossil wood in the early Oligocene-Miocene volcanic deposits in the Czech Republic, Sakala et al. (2010) suggested the following:

Wood type 1: *Liriodendroxylon*, family Magnoliaceae;

Wood type 2: *Laurinoxylon*, family Lauraceae;

Wood type 3: *Platanoxylon*, family Platanaceae;

Wood type 4: *Cercidiphylloxylon*, family Cerciphyllaceae;

Wood type 5: *Ulmus*, family Ulmaceae;

Wood type 6: *Craigia*, family Malvaceae;

Wood type 7: *Coryloxylon*, family Styracaceae.

Modern plant taxonomy (Figure 10):

Kingdom Plantae
Clade Angiosperms
Clade Eudicost
Clade Rosids
Order Fagales
Family Fagaceae
Genus Quercus

Figure 10. The modern *Quercus* and the natural system of classification

Source: United States Department of Agriculture (n.d.).

In summary, the current system of classifying fossil wood does not follow a consistent principle but depends on the views of the researchers. In this study, our approach, research, and classification of fossil wood in Vietnam are based on the results of analyzing the wood tissue structure and comparing it with modern ones. On that basis, the fossil wood tissue types in the territory of Vietnam are proposed.

4.2. Classification of fossil wood according to the criteria of physical-chemical characteristics

Fossil wood is graded according to hardness as one of the criteria for evaluating the quality of wood tissue in use and commerce. Hardness is measured with the Mohs scale. According to the Mohs scale of hardness, the hardness of silicified, opalized, chalcedonized, and agatized wood is about 6-7, and carbonized wood is 3-4.

Table 1. Mohs Hardness Scale

Mineral Hardness Scales		
Mineral	Mohs	Vickers (kg/mm ²)
Talc	1	27
Gypsum	2	61
Calcite	3	157
Fluorite	4	315
Apatite	5	535
Orthoclase	6	817
Quartz	7	1161
Topaz	8	1567
Corundum	9	2035
Diamond	10	10000

Source: Geology.com (2021).

Classification by color criteria: Classification of fossil wood by color is related to its value in jewelry, art, feng shui, and spiritual culture. The color of fossil wood is closely related to the presence of relict organic matter and trace metals (Mustoe, 2008; Mustoe and Acosta, 2016). Common colors in fossil wood are as follows:

- Red: fossil wood containing Fe;
- Orange: fossil wood containing Fe;
- Yellow: fossil wood containing Fe and U;
- Green: fossil wood containing Fe, Cu, Co, Cr, U, Ni;
- Blue: fossil wood containing Cu, Mn, Cp, Cr;

- Violet: fossil wood containing Mn, Fe;
- Purple: fossil wood containing Fe, Mn;
- Brown: fossil wood containing Fe, U;
- Black: fossil wood containing Mn, C, Fe;
- White: fossil wood containing SiO₂;
- Gray: fossil wood containing SiO₂, C.

4.3. Classification by size and monolithic criteria

Determine the aesthetic, commercial, and artistic value of fossil wood based on both color and size criteria. For the same type of fossil wood, the larger the size and the more monolithic, the higher the economic value. Below is the size classification used in commerce:

Table 2. Classification of fossil wood by size

Levels	Size (m ³)	Commercial value
Extra-large	> 2 m ³	Greatest
Large	> 1 m ³	High
Medium-large	50 cm ³ -1 m ³	Average
Medium	10-50 cm ³	Average
Small	2-10 cm ³	Little
Extra-small	< 2 cm ³	Little

5. FOSSIL WOOD IN DISPLAY, FENG SHUI, AND SPIRITUAL ART

(a)

(b)

Figure 11. Fossil wood in display and conservation

Note: a) Petrified log in Paleorrota Geopark, Brazil; b) Cretaceous fossil wood from the Puyanop Petrified Forest, Protected Areas, Ecuador.

Source: "Petrified wood," (n.d).

Exhibits in parks: In many countries worldwide, fossil wood is displayed in parks, preserving the prehistoric natural landscape. In addition, the display of fossil wood in parks also attracts many visitors.

Figure 12. Fossil wood in feng shui art

Note: In a) offices; b) shops; and c) gardens.

Source: Figure 12a) Mỹ Nghệ Hải Minh (n.d.); Figure 12b) Gỗ Thành Vinh (n.d.); Figure 12c) Đời sống pháp luật (n.d.).

Feng shui: An art that appeared in ancient China, bringing about energy flows according to the yin-yang rule. Today, business people often place precious stones, colorful quartz crystals, and agatized trees in their offices and shops, wishing for luck and prosperity in business.

Figure 13. Fossil wood jewelry

Note: a) Bracelet; b) Ring; c) Bead bracelet.

Source: Trangsucvn.

Spiritual culture: In the spiritual culture of the Vietnamese people, agatized wood is considered a protective stone. According to folk beliefs, wearing agate jewelry can reduce conservatism and pressure, mediate quarrels and conflicts, and bring peace, luck, and health to life.

6. CONCLUSION

Although the research and assessment of fossil wood in Vietnam are still limited, five different types of wood have been discovered to date in the Devonian, Triassic, Jurassic, Cretaceous, Paleogene-Neogene, and Pliocene-Pleistocene stratigraphy. They are mold fossils, and silicified, carbonized, carbonified, and jadeized wood. Fossil wood assessment based on paleontological classification criteria using the comparative anatomical method was applied to several fossil wood samples from the Jurassic, Cretaceous, and Neogene strata by French paleontologists (Boureau, 1950a, 1950b, 1952, 1958; Serra, 1966a, 1966b, 1967, 1968, 1969; Boura et al., 2013). Semi-precious and precious fossil wood is sold on the Vietnamese market according to the criteria of hardness, color, and size. Criteria for paleontological classification, geological age, and formation origin of wood have not gained enough suggestion. The research and assessment of fossil wood is an experiment to help paleontologists of the Vietnam National Museum of Nature initially familiarize themselves with the study and assessment of fossil wood samples. In the future, there is hope for more scientific publications on fossil wood by Vietnamese paleontologists.

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