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Exploring Pliocene Vegetation Variability through Wood Fossil Analysis from Jasinga, Indonesia

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ABSTRACT. – Residents of Jasinga, West Java, consistently reported the presence of an abundance of wood fossils. We examined geological settings and wood fossils to investigate the paleovegetation types in the region. This research aims to map the distribution of wood fossils and interpret the paleoenvironment based on paleontological evidence. Lithostratigraphic measurements were performed, followed by a description of wood fossil anatomy in micro-thin section observations, isolation of palynological fossils from the host rock through chemical preparation techniques, and geochemical analysis using X-ray fluorescence spectroscopy. Our findings indicate that the area comprises Pliocene fluvial-volcanoclastic deposits containing several dipterocarp wood fossils, including *Parashoreoxylon*, *Dryobalaonoxylon, Shoreoxylon*, *Anisopteroxylon*, and *Dipterocarpoxylon*. There were also non-dipterocarp wood fossils from Apocynaceae, Combretaceae, Fabaceae, and Olacaceae. Most wood fossils in these deposits were silicified (SiO_2: 92.7 ± 1.88%), preserving the wood tissue structures. Additionally, the wood fossil-rich strata contains fossilized palynomorphs, including pollen fossils from Dipterocarpaceae, Convolvulaceae, and *Florschuetzia*, and spore fossils from *Stenochlaenidites*, *Verrucatosporites*, and *Lygodium*, indicating the presence of a more diverse paleovegetation. These results support the existence of paleotropical rainforests. Our study suggests that paleoclimatic and paleovolcanic settings have significantly shaped the paleotropical rainforest ecosystems in the southern part of Sundaland during the Early Pliocene.

KEYWORDS: Petrified wood, Dipterocarpaceae, Sundaland, Paleobotany, Paleontology

INTRODUCTION

Residents in West Java, Indonesia, have accidentally discovered fossilized woods. However, some locals sell these fossils for profit, often without recognizing their scientific significance. These wood fossils can provide valuable insights into the region’s natural history, contribute to studies on paleovegetation, and enhance our understanding of geological processes. In response, we formed a systematic investigation to gain a comprehensive understanding of the distinctiveness and significance of these wood fossils. Our focus is on analyzing paleovegetation variability within the context of the region’s geological history. Furthermore, we aim to raise awareness among local governments and researchers to promote the conservation of these wood fossils in the area.

Previous studies have attempted to research this region (Berger, 1923; Mandang and Martono, 1996; Srivastava and Kagemori, 2001; Mandang and Kagemori, 2004; Fauzielly et al., 2017). However, the research is still limited to the fossils found, and there has yet to be much follow-up research afterward to reveal more about the geological setting for a proper understanding. Therefore, in this study, we tracked a location that we considered minimally disturbed by anthropogenic activity and more ideal for geological mapping. We selected Jasinga as the study area (Fig. 1). Jasinga is included in the Bogor Zone, according to the physiographic map of Java (Martodjojo, 1984). The presence of structural-folded hills and remnants of several morphological features of the volcanoes characterizes this zone.

This study aims to map the distribution of wood fossils and interpret the paleoenvironment based on paleontological evidence. We examined the presence of wood fossils and fossilized palynomorphs in the rock strata. Fossils were traced to the parent rock in the study area. Thus, geological mapping is crucial for determining the position and relative age of fossils discovered in rock strata. Geochemical analyses of the wood fossils were performed to understand the characteristics and geological processes that have occurred.

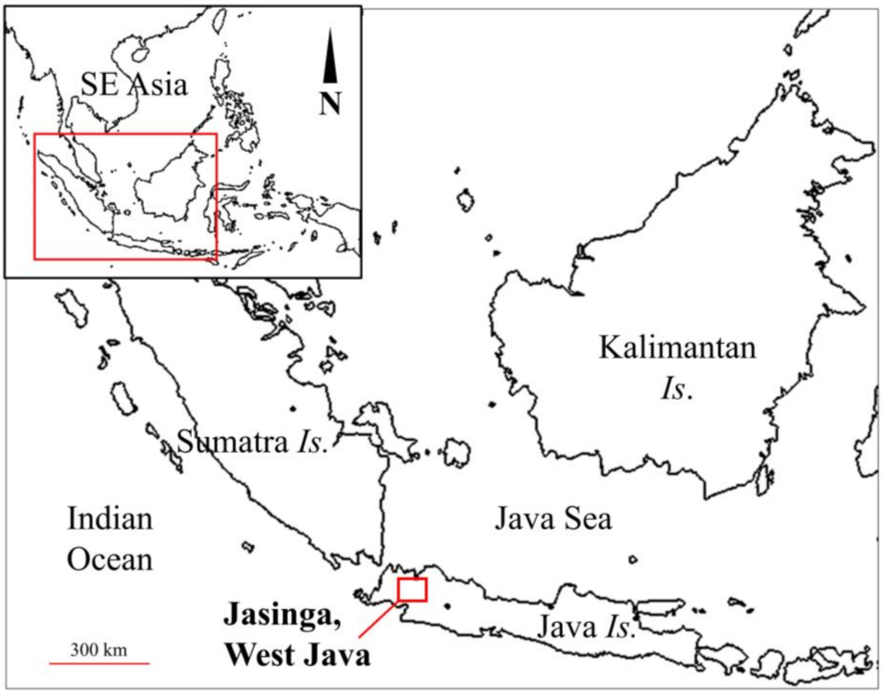

FIGURE 1. Location of Jasinga, West Java, and its position in Southeast Asia.

MATERIALS AND METHODS

Geological Mapping and Sample Collections. The fieldwork was conducted in Jasinga, West Java, Indonesia, approximately 54 km southwest of Jakarta. We referred to the Leuwiliang Geological Map (Sujatmiko and Santosa, 1992) to track the distribution of geological formations and their relative ages in the research area. The lithostratigraphic profiles of the area were measured along the Ciherang River, which is approximately 8.1 km long. The strike-dips of the rock strata were measured using a geological compass. The rock units were grouped into several facies based on their lithological characteristics, referring to Nichols (2009). The wood fossils found in the rock layers were tagged using the Global Positioning System (GPS) and collected. The basemap was created using the Digital Elevation Model (DEM) published by BIG-RI (2019).

Wood Fossils Description. Wood fossils were prepared for thin-section observations, including cross-sectional, tangential, and radial orientations. The thin sections were examined under a non-polarized microscope to identify the remnant preserved microscopic wood anatomy, and a polarized microscope was used to determine the minerals in the fossil. Taxonomic identification was based on the International Association of Wood Anatomists (IAWA) for wood anatomy identification keys (de Pernia and Miller, 1991; IAWA Committee, 1989). We also compared the described anatomy of the wood fossils in this study with the identification features of related wood taxa in the InsideWood database (InsideWood, 2004; Wheeler, 2011; Wheeler et al., 2020) and modern timber of Southeast Asia and the Western Pacific (Ogata et al., 2008).

X-Ray Fluorescence. The geochemical composition of the wood fossils was analyzed using X-Ray Fluorescence (XRF) spectroscopy. XRF analysis was conducted using a Malvern Panalytical-Epsilon 4 at the National Research and Innovation Agency - Mining Technology Laboratory in Lampung, Indonesia. Nine wood fossils collected from the rock units were powdered into 200-mesh grains. The XRF results were analyzed to obtain the mean and standard deviation values of the major oxides.

Fossilized Palynomorph Preparation. Fossilized palynomorphs were extracted from rock units that mostly contained wood fossils. Additionally, fine grains of carbonaceous-paleosol were preferred for palynomorph fossil extraction to ensure more successful preparation. The fossilized palynomorph preparation was conducted at the Palynology Labs of the Indonesian Geological Survey Agency. The rock samples were prepared using chemical treatment techniques including 40% HF, heated 10% KOH, mixed acid of $HCl+HNO_3$ (1:1), and concentrated $ZnCl_2$ to remove silica, carbonate, heavy metals, and

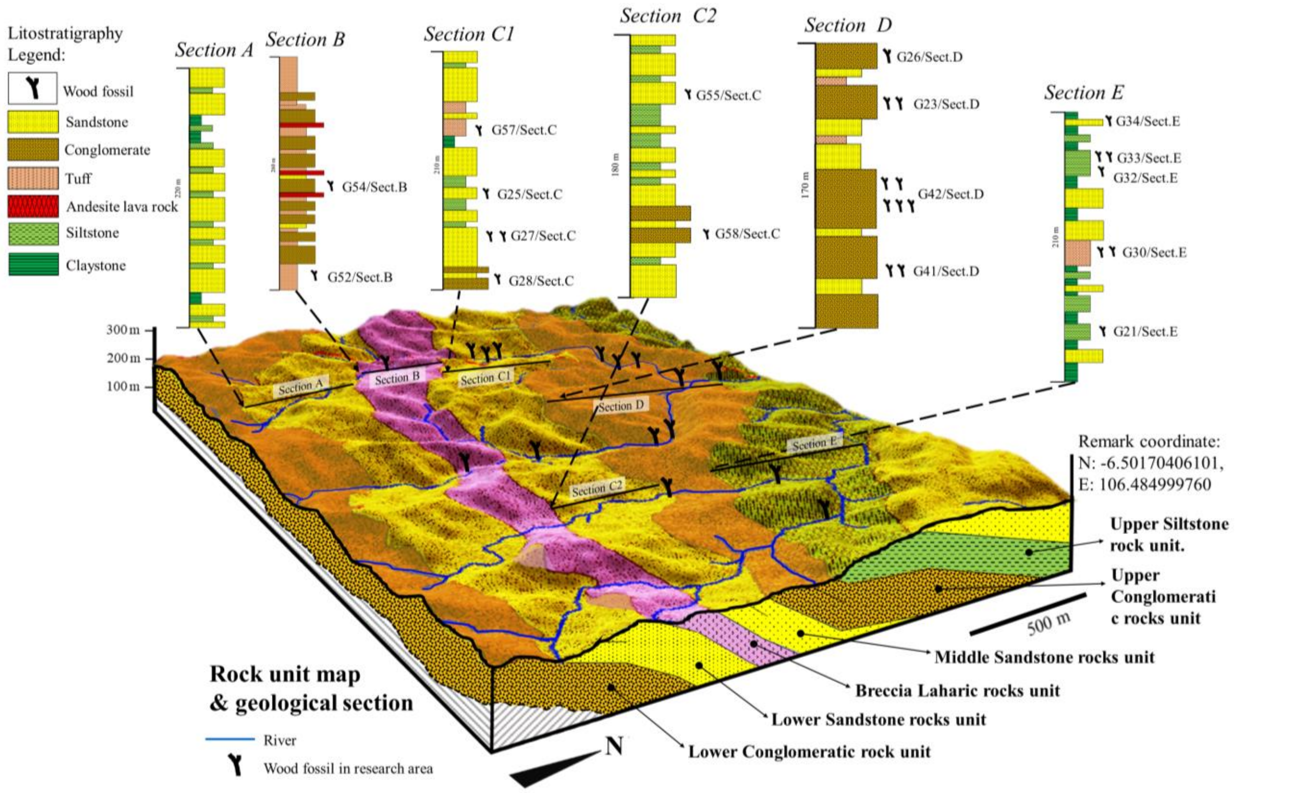

FIGURE 2. 3D Model of the geological map of the study area. The research area has been divided into six distinct rock units based on lithostratigraphic sections.

humic acid residues, refer to Sukapti and Dewi (2023) and Yulianto et al. (2005). Mixtures of H_2SO_4 and $(CH_3CO)_2O$ were used for acetolysis as described by Erdmant (1943), Faegri and Iversen (1975), and Germeraad et al. (1968). This method eliminated recent plant palynomorphs, leaving only fossilized palynomorphs, including pollen and spore fossils. PalDat (2021), an online palynological database, is referred to in determination.

RESULTS

Lithostratigraphy. The study area is divided into seven rock units. All rock units exhibit a dip direction that tends northeast (NE). The overall stratigraphic position of the rock units can then be determined from the oldest to youngest strata (see Fig. 2). The data from each lithostratigraphic section aims to provide an understanding of the facies. Wood fossils were present in four rock units: The Breccia Laharic rock unit (oldest), the Middle Sandstone rock unit, the Upper Conglomeratic rock unit, and the Upper Siltstone rock unit (youngest). Wood fossils were found attached to the sedimentary rock, and some were easily loosened (see Fig. 3). Tuffaceous beds are also present in these rock units. The measured lithostratigraphic profile of each rock unit, including the textures of the rock and the presence of fossils, revealed different facies in each rock unit. These facies characteristics are key to explaining the paleodepositional environments related to geological processes. A more detailed description of each rock unit is presented in the following section.

Lower Conglomeratic Rock Unit. It is located in the southernmost part of the study area and consists of conglomerate beds. The thickness of each bed ranges from 100 to 200 cm. The conglomerate grains vary in size from granules to pebbles, exhibiting rounded shapes and an open texture. The matrix comprises lithic materials in sand-sized particles and contains several subspherical andesitic clastic fragments in cobbles-sized. Sandstone beds (10 to 30 cm thickness) were found between the conglomerate beds. Wood fossils are not present in this rock unit. These rocks have dip angles ranging from 19° to 32° with northeast (NE) dip directions. The presence and continuity of conglomerates along the strike direction suggest that this unit is the oldest rock unit in the study area. It overlies the Late Miocene Bojongmanik Formation with unconformities. This rock unit likely formed in depositional environments with medium-to-high-energy

FIGURE 3. Selected documentation of the outcrop and wood Fossils in Jasinga (red arrow). Outcrop of the Breccia Laharic rock unit (A) with wood fossils laying on the rock bed (B), some recovered (C). Outcrop of paleovolcanic-ash and carbonaceous beds covered by paleosol (D); log of wood fossil (E) in the Middle Sandstone rock unit. Logs of wood fossils in the Upper Conglomeratic rock unit (F). Recovered wood fossil from the Upper Siltstone rock unit (G).

flow facies. The presence of andesitic clast fragments in this rock unit indicates the occurrence of transitional paleovolcanic islands, considering that the Bojongmanik Formation mainly formed in shallow marine environments, as demonstrated by Sujatmiko and Santosa (1992).

Lower Sandstone Rock Unit. It primarily consists of sandstone beds. These beds vary in thickness, ranging from 25 to 75 cm for each layer. The sand grains within these beds are of medium to coarse size. Interspersed between the sandstone beds are layers of siltstone and claystone, with a thickness of approximately 5 to 15 cm. Notably, mudcrack-like structures are frequently observed in the claystone beds. The overall bedding orientation in this rock unit tends to have strike directions between 255° to 335°, with dip angles ranging from 19° to 37° toward the northeast (NE) to northwest (NW). Interestingly, no wood fossils are present within this rock unit. The facies' characteristics suggest that they formed in depositional environments with low-energy flow fluvial conditions.

Breccia Laharic Rock Unit. It primarily consists of volcanoclastic deposits. These deposits include fine tuff beds (5 to 20 cm) and tuffaceous sandstone to lapilli beds (20 to 30 cm). Additionally, this rock unit contains beds of vesicular andesitic igneous rock (with a thickness of 50 to 100 cm) and volcanic breccia (bed thickness: 150 to 250 cm). The vesicular structures observed in the andesite beds indicate surface lava flow crystallization, likely resulting from eruptions by a near-paleovolcano. While wood fossils are present, they are rare. These fossils can be found within the beds of tuffaceous sandstone, tuff-lapilli, and volcanic breccia (as shown in Fig. 2A-C). Notably, the wood fossils are mostly fully silicified and harder than usual, measuring up to seven Mosh scales in hardness. The wood fossil fragments range from 20 to 60 cm in length. The estimated thickness of this rock unit is 75 to 100 m. Its northeast (NE) dipping directions correspond to dip angles ranging from 13° to 45°. Overall, the lithostratigraphy and the presence of wood fossils in this rock unit suggest that it represents the lahar channel facies, which were deposited in the valley of near-vegetated paleofluvial-volcanic environments.

The Middle Sandstone Rock Unit. It primarily consists of sandstone beds, with each bed thickness 50 to 100 cm. Intercalated between these sandstone beds are layers of siltstone and claystone, which are approximately 5 to 15 cm thick. In certain sections, you can also find conglomerate beds and andesitic breccia, which exhibit similar orientations to the sandstone beds. Generally, the sandstone beds have dip angles ranging from 24° to 39°, with directions toward the northeast (NE). Additionally, there are sequences of sandy siltstone dominated by carbonaceous grains. These sequences lie just below the ash-tuff beds (which represent paleovolcanic ash) and exhibit grain sizes ranging from clay to medium-sized particles. At the base of these beds, a paleosol/paleosoil layer (as shown in Fig. 2D), which shares relatively similar orientations with the lower part of the bed sequences (approximately N303°E/32°NE). Wood fossils are most frequently found in this rock unit, often in the form of logs (as depicted in Fig. 2E). This outcrop provides evidence of a hot volcanic ash-fall episode resulting from near-palaeovolcanic eruptions. The volcanic ash settled into paleo-vegetated environments, scorching the organic tissues of vegetation and leaving behind carbonaceous charcoal before eventually burying the soil. The facies within this rock unit suggest formation in low-energy flow fluvial areas associated with woody-vegetated environments. Furthermore, near-paleovolcanic activities played a crucial role in the deposition and fossilization of woody vegetation during this episode.

The Upper Conglomeratic Rock Unit. It primarily consists of conglomerate beds. Each conglomerate bed has a thickness ranging from 100 to 200 cm. The grain sizes within these beds vary from pebbles to cobbles. These grains are generally round to sub-rounded and are commonly moderately sorted, with coarse sand matrices. Notably, wood fossils are predominantly silicified in this rock unit (as depicted in Fig. 2F), although a few carbonaceous wood fossils can also be found. The wood fossils often exhibit log shapes, with maximum lengths ranging from 30 to 90 cm. Interestingly, some of these logs align parallel to the rock bed. The beds dip at 14 to 26° to the northeast (NE). Overall, the thickness of this rock unit spans from 200 to 250 m. The facies characteristics suggest that this unit represents paleodepositional environments associated with high-energy fluvial flow areas in woody-vegetated alluvial fans.

The Upper Siltstone Rock Unit. It primarily consists of siltstone. Intercalated between the dark grey siltstone beds are layers of dark brown to grey claystone and fine to medium-grain sandstone. These sandstone beds frequently occur alongside the siltstone layers. The dip angle of the beds ranges from 10° to 25° in the northeast (NE) direction. Some sequences reveal coarse tuffaceous sandstone beds that run parallel to the siltstone beds (oriented at N 331°E/20°NE). Within this rock unit, fragmented wood fossils have undergone silicification (as shown in Fig. 2F). Some parts of these fossils exhibit a carbonaceous nature and are quite fragile. Many of these wood fossils can be easily detached from the rock beds. The facies observed in this rock unit suggest low-energy fluvial environments that may have been influenced by distal paleovolcanic drainage, resulting in the deposition of fluvial-volcanoclastic sediments.

Jasinga Wood Fossils Anatomy. Most of the wood fossils in the Jasinga have already been silicified. A few of the specimens were carbonaceous. Silicified wood fossils have rigid woody textures, with the hardness level of these specimens ranging from 6.5 to 7.0 on the Mohs scale. In contrast, carbonaceous wood fossils tend to be fragile, with hardnesses below 3.0 on

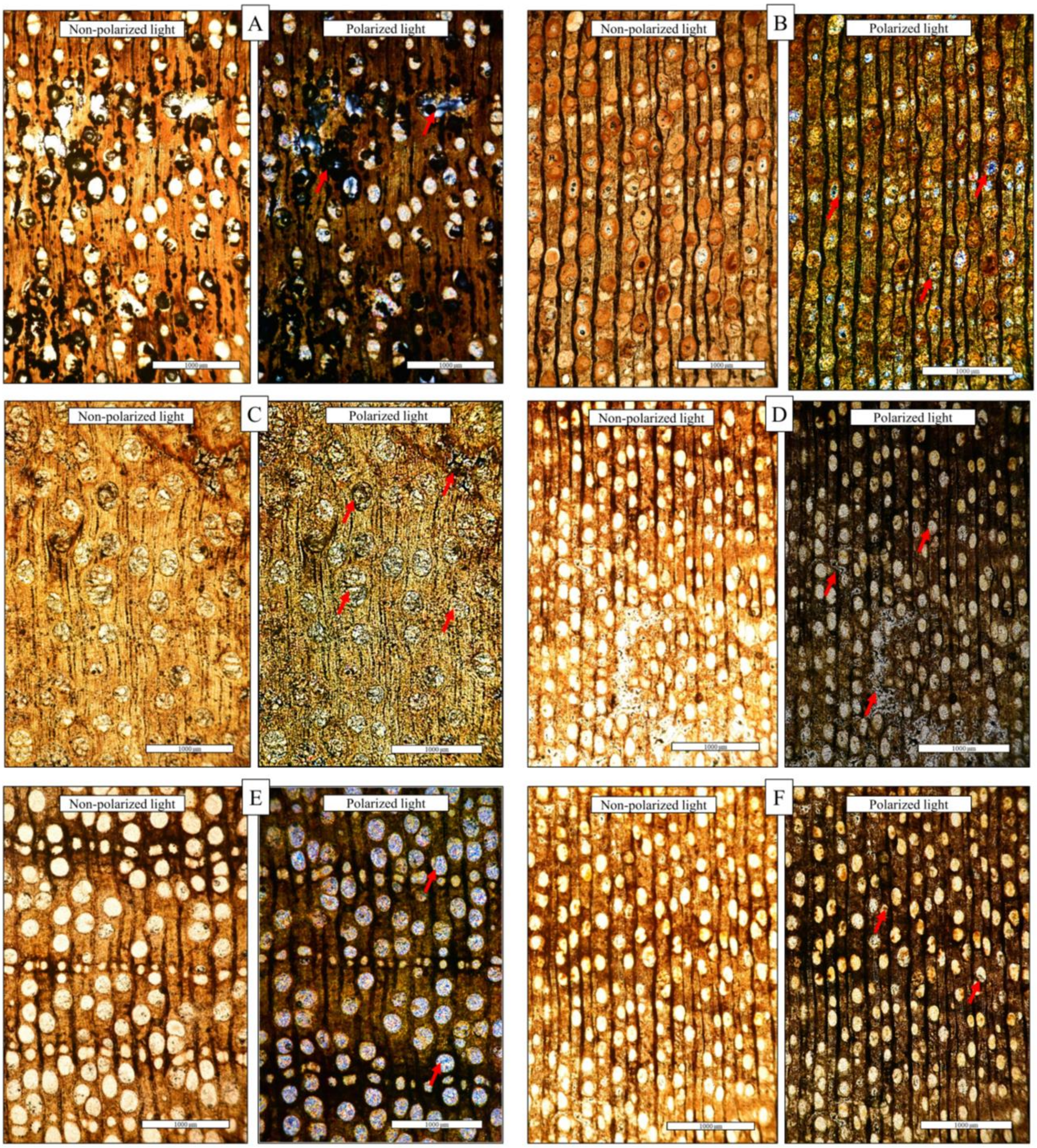

FIGURE 4. Collection of Jasinga wood fossil thin-sections observed under a non-polarized and polarized light microscope, showing permineralization (red arrows). *Alstonioxylon* G52/Sect.B (A); *Anisopteroxylon* G54/Sect.B (B); *Terminalioxylon* G55/Sect.C (C); *Dipterocarpoxylon* G56/Sect.C (D); *Dryobalanoxylon* G57/Sect.C (E); *Dipterocarpoxylon* G58/Sect.C (F). Scale: 1000 µm (white bar).

the Mohs scale. Unfortunately, not all anatomical structures in wood fossils are clearly observed in non-polarized and polarized microscopes. Some silicified wood fossils were fully permineralized, concealing the original anatomical features. Similarly, in carbonaceous wood fossils, the fragile condition of wood fossils causes breakage of the wood tissue structure at the microscopic scale, making it unidentifiable. Features such as intervessel pits and vessel-ray pits tend to be indistinctive in the specimen due to silicification. Nevertheless, we successfully collected some specimens with well-preserved wood anatomical structures that were clearly observed and taxonomically distinguishable to the genus level (Fig 4 to Fig 6). We collected 26 specimens from each rock unit and described ten taxa. Interestingly, most wood

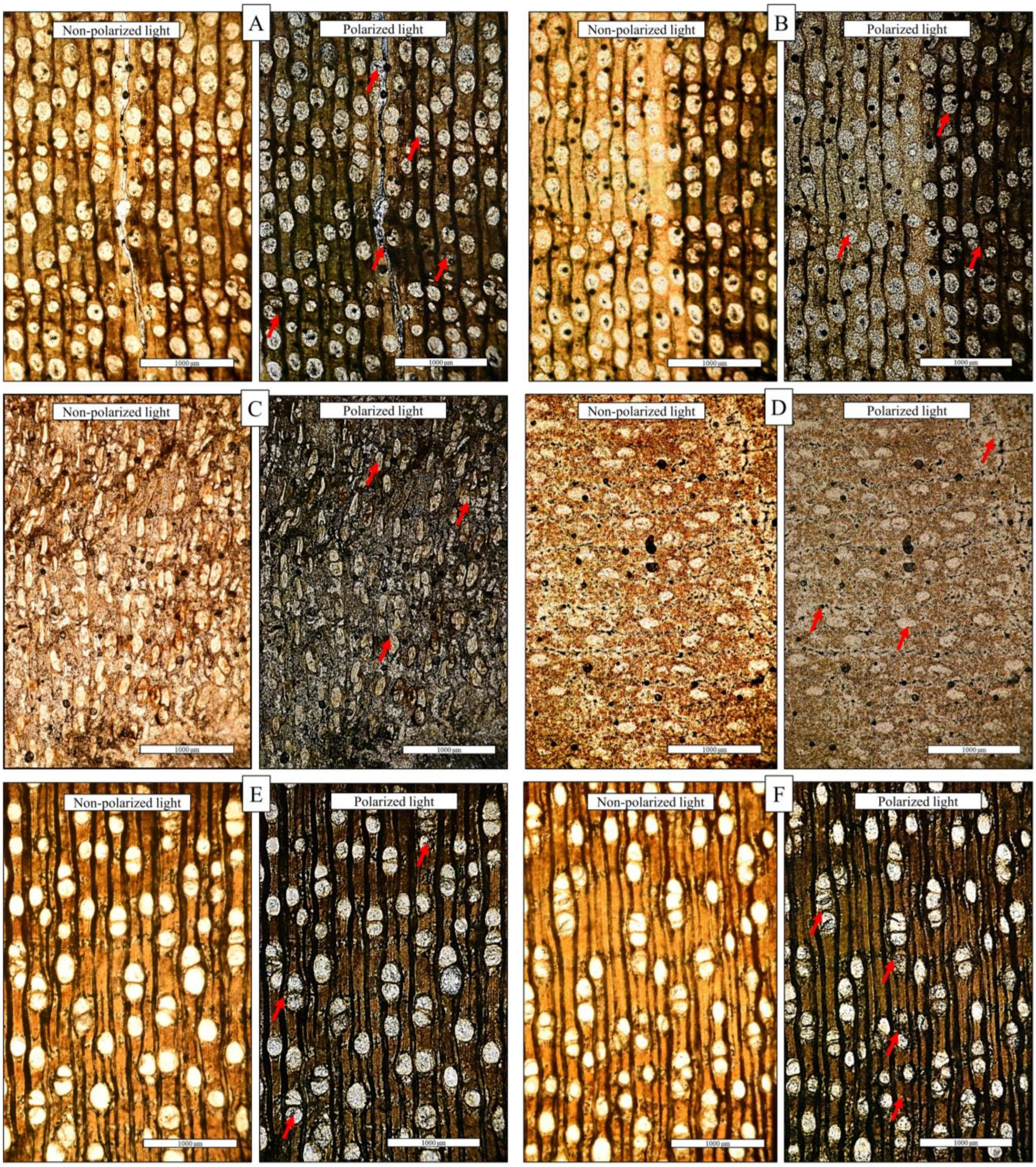

FIGURE 5. Additional collection of Jasinga wood fossil thin-sections observed under a non-polarized and polarized light Microscope, also demonstrating permineralization (red arrows). *Dryobalanoxylon* G23/Sect.D (A); *Parashoreoxylon* G42/Sect.D (B); *Ochanostachixylon* G30/Sect.E (C); *Dichrostachyoxylon* G32/Sect.E (D); *Shoreoxylon* G33/Sect.E (E); *Shoreoxylon* G34/Sect.E (F). Scale: 1000 μm (white bar).

fossils are filled with silica oxides in the form of opal, chalcedony, and quartz, particularly in wood vessels (Fig. 7). Detailed descriptions of each taxon are provided in the following paragraphs.

Family Apocynaceae, Genus *Alstonioxylon* Mandang and Martono, 1996: Growth rings are distinct. Vessels are diffuse-porous, occurring in multiple to clustered arrangements, with diameters ranging from 100 to 200 μm. The density of vessels is 5 to 10 vessels/mm^2. Parenchyma cells are primarily diffuse, irregularly shaped, and moderately abundant. Rays are mostly uniseriate, composed of 1 to 3 cells,

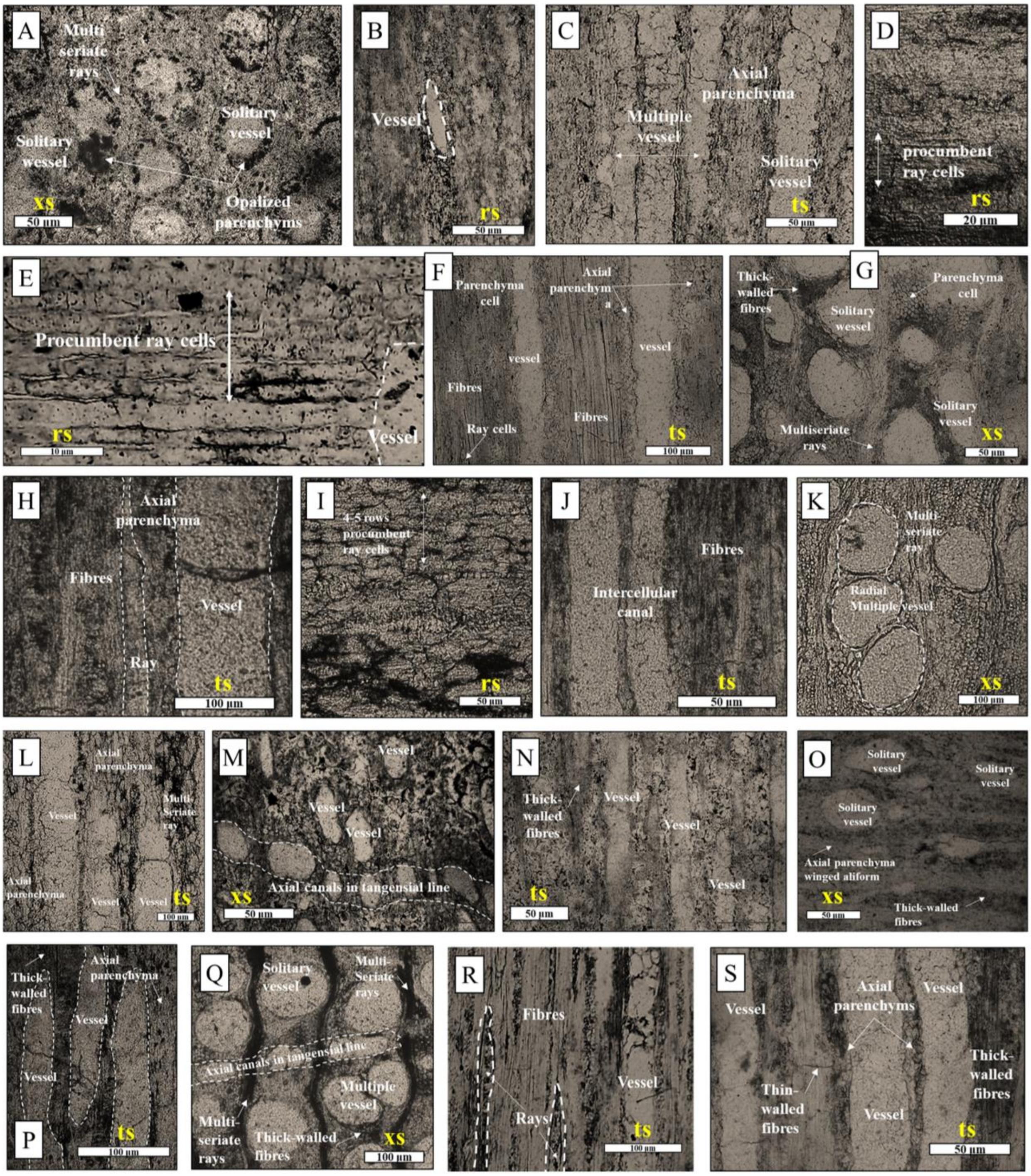

FIGURE 6. Described features of microscopic wood anatomy in different sections (xs: cross-section; ts: tangential-section; rs: radial-section): *Alstonioxylon* (A-B); *Anisopterteroxylon* (C-D); *Terminalioxylon* (E-F); *Dipterocarpoxylon* (G-H), *Dryobalanoxylon* (I-J); *Parashoreoxylon* (K-L); *Ochanostachysoxylon* (M-N); *Dichrostachyoxylon* (O-P); *Shoreoxylon* (Q-S). Scale: white bar.

occurring at a density of 4 to 12 rays/mm. They exhibit heterocellular characteristics. Fibers are moderately thick-walled and occur in small groups or more continuous bands (see Fig. 4A and Fig. 6A-B). These characteristic are analogous to the modern genus *Alstonia*, within the family Apocynaceae. The taxon is present in the Breccia Laharic rock unit. Specimen: G52/Sect.B.

Family Dipterocarpaceae, Genus *Anisopteroxylon* Ghosh and Kazmi, 1958: Growth rings are absent; vessels are diffuse, mostly solitary, oval in shape, with diameters ranging from 150 to 300 µm, occurring at a density of 4 to 8 vessels/mm². Parenchyma cells are sparse to moderately abundant, sometimes aliform, forming diffuse short lines between rays. The rays come in two sizes, mostly multiseriate, consisting of 5 to 10 cells per ray, with less than 4 rays/mm, exhibiting

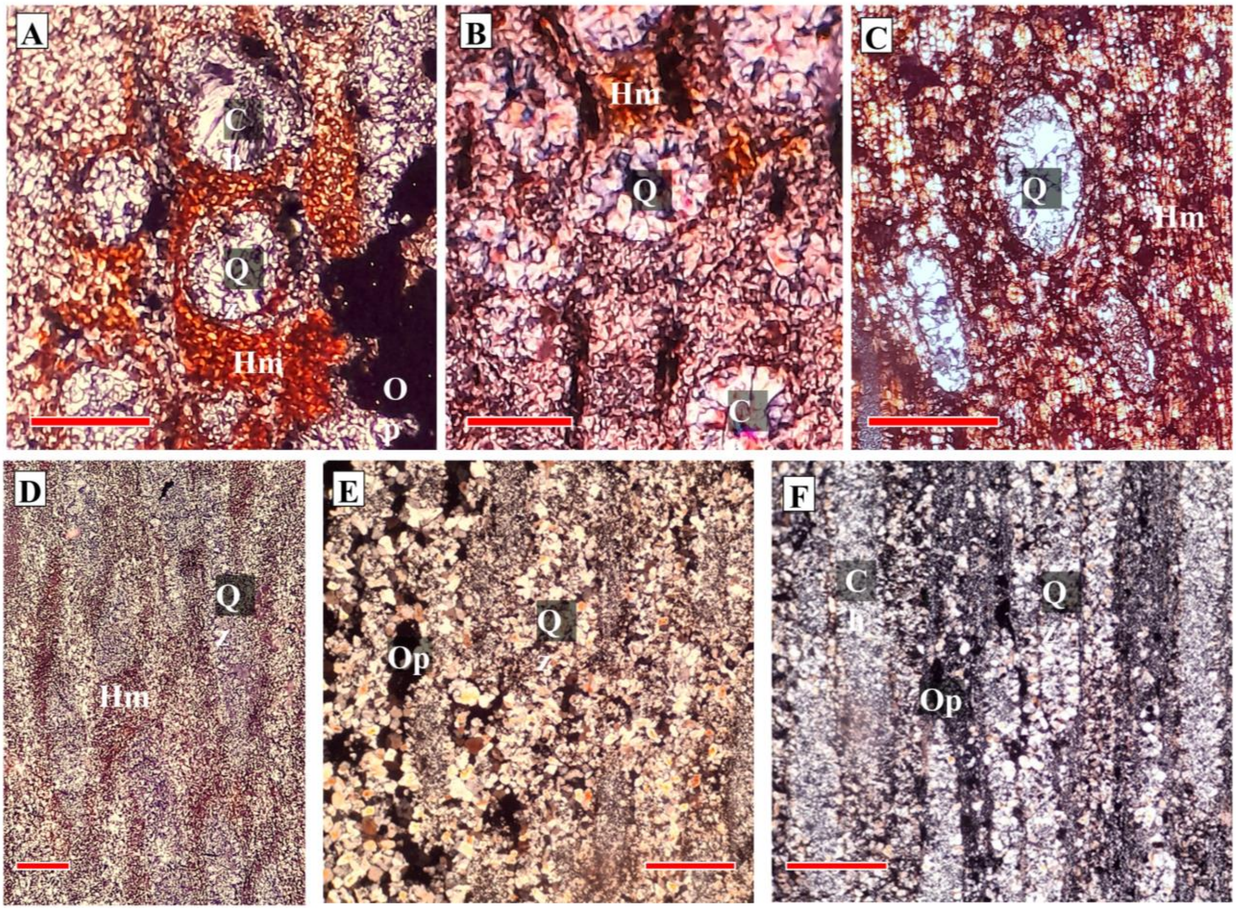

FIGURE 7. Thin sections of wood fossils under polarized light microscopy reveal vessels filled with silica pxides Such as Quartz (Qz), Chalcedony (Ch), and Opal (Op). Additionally, iron oxides such as Hematite (Hm) occur in the fibers and parenchyma. It observed in cross-sections of *Shoreoxylon* (A), *Dipterocarpoxylon* (B), *Dichrostachyoxylon* (C); radial section of *Shoreoxylon* (D); tangential sections of *Dryobalanoxylon* (E), and *Parashoreoxylon* (F). Scale: 200 µm (red bar).

heterocellular characteristics. Fibers are thin to moderately thick-walled and occur either in small groups or as more continuous bands (see Fig. 4B and Fig. 6C-D). These characteristic are analogous to the modern genus *Anisoptera*, within the family Dipterocarpaceae. The taxon is present in the Breccia Laharic and Upper Conglomeratic rock units. Specimens: G54/Sect.B and G26/Sect.D.

Family Combretaceae, Genus *Terminalioxylon* Schönfeld, 1947: Growth rings are present. Vessels are diffuse-porous, occurring in multiple to clustered arrangements, with up to 4 vessels per cluster. They are oval-shaped, ranging from 150 to more than 200 µm in diameter, and occur at a density of less than 20 vessels/mm². Parenchyma cells are vasicentric, aliform (wing-shaped), and sometimes confluent. Rays consist of 1 to 3 cells and occur at a density of more than 4 rays/mm. The fibers are moderately thick-walled (see Fig. 4C and Fig. 6E-F). These characteristics are analogous to the modern genus *Terminalia*, within the family Combretaceae. The taxon is present in the Middle Sandstone rock unit. Specimen: G55/Sect.C.

Family Dipterocarpaceae, Genus *Dipterocarpoxylon* Holden, 1916: The growth ring boundaries were indistinct. Vessels are diffuse, exclusively solitary, with diameters ranging from 100 to 300 µm, and vessel frequencies ranging from 5 to 20 vessels/mm². The axial parenchyma is vasicentric. Ray cells are commonly 4 to 10 seriate. Body ray cells are procumbent, with upright and square marginal cell rows. The fibers are thin to thick-walled (see Fig. 4D, F; Fig. 6G-H). These characteristics are analogous to the modern genus *Dipterocarpus*, within the family Dipterocarpaceae. The taxon is present in the Middle Sandstone rock unit. Specimens: G56/Sect.C and G58/Sect.C.

Family Dipterocarpaceae, Genus *Dryobalanoxylon* Berger, 1923: Growth rings are not clearly defined but may be associated with irregularly spaced aliform parenchyma bands. Vessels are diffuse-porous, solitary, and round to oval, ranging from medium to moderately large (150 to more than 200 µm). The vessel frequencies range from 10 to 16 vessels/mm². Parenchyma cells are moderately abundant, irregularly

TABLE 1. Geochemical analysis of wood fossils in Jasinga, West Java (n.d.: not detected).

Sample	SiO_2	Total iron	Al_2O_3	K_2O	MgO	CaO	P_2O_5	TiO_2	Other
Wood fossil* (n: 9)	92.7 % ± 1.88	3.4 % ± 2.10	1.8 % ± 0.41	0.1 % ± 0.12	n.d.	1.1 % ± 1.05	0.7 % ± 0.03	0.65 % ± 0.04	0.1 % ± 0.04

*mean value with standard deviation

spaced, and arranged in aliform bands, specifically paratracheal. Rays consist of 4 to 10 seriate cells, usually occurring at a density of 5 to 10 rays/mm. Fibers are typically thinner to moderately thick-walled (see Fig. 4D; Fig. 5 A; Fig. 6 I-J). These characteristics are analogous to the modern genus *Dryobalanops*, within the family Dipterocarpaceae. The taxon is present in the Middle Sandstone and Upper Conglomeratic rock units. Specimens: G57/Sect.E and G43/Sect.D.

Family Dipterocarpaceae, Genus *Parashoreoxylon* Mandang and Martono, 1996: Growth rings are absent. Vessels are diffuse, mostly solitary, and mostly round in shape, ranging from 200 to 300 µm, with a frequency ranging from moderate to low (3 to 5 vessels/mm²). Parenchyma is mostly diffuse, moderately abundant to sparse, and occurs in paratracheal, vasicentric, aliform, or confluent arrangements. Rays are mostly multiseriate, typically 3 or 4 cells wide and around 1.0 mm in height, usually occurring at a density of 5 or 6 rays/mm, and exhibit heterocellular characteristics. Fibers are moderately thick-walled (see Fig. 5B; Fig. 6K-L). These characteristics are analogous to the modern genus *Parashorea*, within the family Dipterocarpaceae. The taxon is present in the Middle Sandstone and Upper Conglomeratic rock units. Specimens: G28/Sect.C and G42/Sect.D.

Family Olacaceae, Genus *Ochanostachysoxylon* Mandang and Martono, 1996: Growth rings are indistinct; vessels are diffuse-porous, occurring in multiple to clustered arrangements, with up to 4 vessels per cluster. They are oval-shaped, ranging from 50 to 200 µm, and appear at a density of 5 to 40 vessels/mm². Parenchyma cells are primarily diffuse, irregular in shape, and moderately abundant. Rays consist of 1 to 3 cells with elongated or rectangular cell shapes, occurring at a density of more than 12 rays/mm. The fibers are moderately thick-walled (see Fig. 5C; Fig. 6M-N). These characteristics are analogous to the modern genus *Ochanostachys*, within the family Olacaceae. The taxon is present in the Upper Siltstone rock unit. Specimens: G32/Sect.E.

Family Fabaceae, Genus *Dichrostachyoxylon* Müller-Stoll and Mädel, 1967: Growth rings are semi-distinct; vessels are diffuse-porous, solitary, and ellipse-shaped, with 100 to 200 µm diameters. The vessel frequencies range from 5 to 20 vessels/mm². Parenchyma is winged and aliform. Rays are indistinctive. The fibers are very thin-walled (see Fig. 5D; Fig. 6O-P). These characteristics are analogous to the modern genus *Dichrostachys*, within the family Fabaceae. The taxon is present in the Upper Siltstone rock unit. Specimen: G21/Sect.E.

Family Dipterocarpaceae, Genus *Shoreoxylon* Berger, 1923: Growth rings are present but sometimes indistinct. Vessels are generally diffuse, mostly solitary, and some are multiple. They are medium to moderately large (150 to 200 µm) with frequencies of 4 to 10 vessels/mm². Parenchyma is sparse to moderately abundant, and axial parenchyma is mostly aliform and paratracheal. The ray width consists of 4 or 5 cells, with a height of 50 to 150 µm, and usually 5 or 6 rays/mm. The fibers are thin-walled, mostly libriform, and present in small groups (Fig. 5D-E; Fig. 6 Q-S). These characteristics are analogous to the modern genus *Shorea*, Family Dipterocarpaceae. Taxa presence is observed in the Upper Silstone rock unit; specimens: G34/Sect. E and G33/Sect.E.

Geochemistry of Wood Fossils. The nine wood fossils from different rock units indicate that the specimens had already undergone silicification. XRF results showed that the w/w mean SiO_2 content in the wood fossils was 92% ± 1.88. There is a slight deviation among the samples, suggesting a consistent value even though they belong to different rock units. The remaining compositions include iron, Al_2O_3, K_2O, CaO, P_2O_5, and TiO_2 (Table 1). Regarding the other oxides, the standard deviation of non-silica oxides is relatively large compared to their mean values, likely influenced by the specific characteristics of the host rock. The condition of silicification was also confirmed by the rigid stony appearance, with a hardness level of 6.5 to 7.0 on the Mohs scale. Polarization microscopy revealed that silica filled the vessel lumen during fossilization and crystallized into opal, chalcedony, and quartz (Fig. 7). Additionally, hematites (iron oxide minerals) were seemingly accumulated in the fibers and parenchyma.

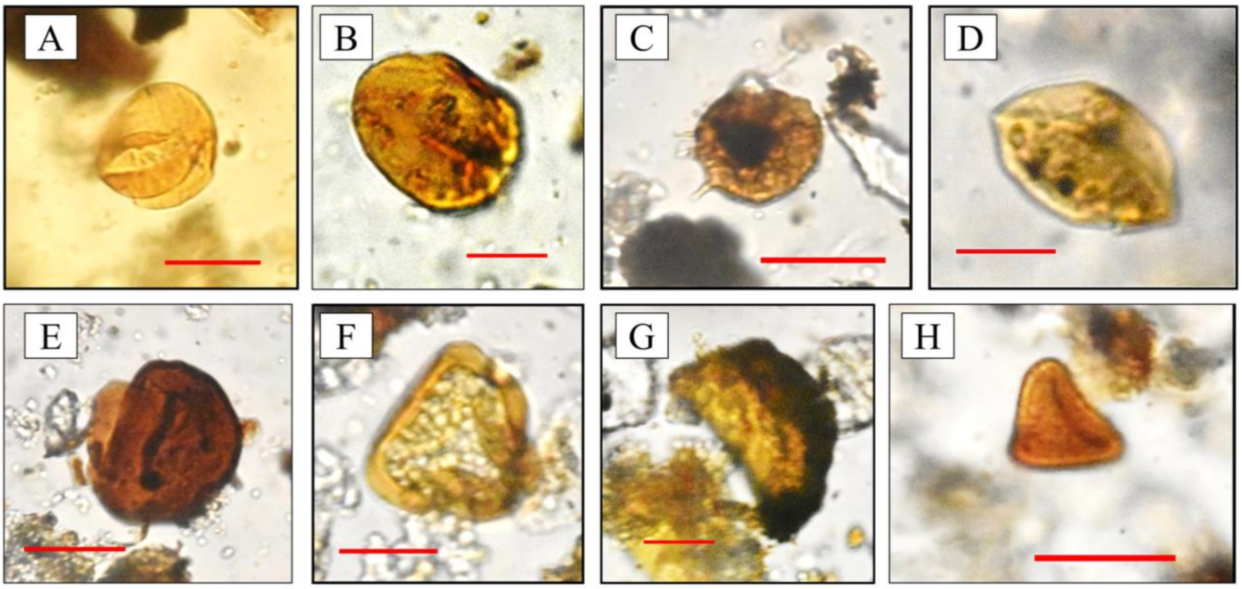

FIGURE 8. Fossilized palynomorphs found in very-fine sedimentary rock of the Middle Sandstone rock unit, Jasinga, West Java. An oblique-polar view of Dipterocarpaceae pollen (A), and its equatorial view (B); Spiky pollen of Convolvulaceae (C); *Florschuetzia meridionalis* (D); another *Florschuetzia* (E); and several spores of *Stenochlaenidites* (F); *Verrucatosporites* (G), and *Lygodium* (H). Scale: 15 µm (red bar).

Fossilized Palynomorphs. Palynomorph fossils were successfully retrieved from the paleosol beds in the Middle Sandstone rock unit (Fig. 2D). This accomplishment was feasible because the Middle Sandstone rock unit exhibited more diverse wood fossils than the others. Additionally, volcanic ash-covered paleosoil beds contribute to preserving palynomorph structures during fossilization processes. Six palynomorph types were identified, including pollen types from Dipterocarpaceae, Convolvulaceae, *Florschuetzia*, and spore types such as *Stenochlaenidites*, *Verrucatosporites*, and *Lygodium* (Fig. 8). Descriptions of fossilized palynomorphs are provided in the following paragraph.

Dipterocarpaceae *pollen-type*. It is relatively large, oval-elliptical, measuring 40 to 80 µm in length and 30 to 60 µm in width. The pollen grains exhibit distinct tri-radiate Y-shaped apertures and longitudinal ridges (see Fig. 8A-B). These characteristics closely resemble modern dipterocarp pollens (Hamilton et al., 2019).

Echinate Convolvulaceae *pollen-type*. The pollen grains have oval-shaped structures with spines, ridges extending from the surface, and germinal pores. The grain diameters range from 20 to 50 µm (see Fig. 8C). The spiky features of Convolvulaceae pollen are common in the modern genus *Ipomoea*, which is associated with near-shore environments (Manvar and Desai, 2013).

***Florschuetzia pollen-type*.** The pollen grains have triangular shapes, are present as single grains, isolpolar, and have a single aperture ranging from 15 to 30 µm. The grains are thick-walled, measuring about 2 µm, and are equatorially ornamented (see Fig. 8D-E). *Florschuetzia* is an extinct flowering plant analogous to the modern genus *Sonneratia*; it had a wide distribution before the Pleistocene (Mao and Foong, 2013). Some researchers have found this pollen in Pliocene deposits in several Java basins (Suedy et al., 2012; Rachman and Winantris, 2023). Florschuetzia indicates the presence of lowlands and coastal paleoenvironments.

***Stenochlaenidites spore-type*.** This palynomorph has a spheroidal shape, ranging from approximately 20 to 40 µm in diameter. The grain surface is typically covered in a series of thick layers, giving it a bristly appearance. The aperture is located at the equator (see Fig. 8F). *Stenochlaenidites* are extinct ferns found in the Pliocene sedimentary rock of southeastern Asia (Wilf et al., 2022).

***Verrucatosporites spore-type*.** Spores are generally spheroidal or slightly elongated, with a thick, rough surface covered in small warts (verrucated). Their grain diameters range from approximately 25 µm to 50 µm (see Fig. 8G). *Verrucatosporites* are associated with non-arboreal environments (Hapsari and Sukarsa, 2012).

***Lygodium spores-type*.** It has a longitudinal aperture and tends to have smooth triangular shapes with straight sides. The length is approximately 10 µm, and perforations are visible on the perispore surface (see Fig. 8H). *Lygodium* is a group of pteridophyte ferns that thrive in tropical climates (Giacosa et al., 2013; Humphreys et al., 2017).

DISCUSSION

Stratigraphy in Jasinga. Most of the Jasinga area in West Java is composed of volcanoclastic-sedimentary rock, which is part of the Genteng Formation. According to the Leuwiliang Geological Map Sheet (Sujatmiko and Santosa, 1992), the Genteng Formation likely formed during the Early Pliocene or Zanclean Stage (approximately 5.3 to 3.6 million years ago). The rocks in this area exhibit inclining, as indicated by the measured strike and dip values. Specifically, the strike and dip values reveal older strata in the relatively southwestern part and continuously expose younger strata toward the northeast. At least five distinguishable rock units can be identified based on their position, relative age, and facies. Interestingly, wood fossils are arranged in the younger strata within four of these rock units. Beyond indicating the relative age of the strata, this condition also suggests that local tectonic events have influenced the dynamics of paleoenvironmental evolution during geological processes, particularly during the early deposition of the Genteng Formation since the Early Pliocene.

The Genteng Formation overlays the Bojongmanik Formation. The Bojongmanik Formation represents an episode of shallow marine sediment to marine carbonate deposition during the Late Miocene. Notably, the presence of wood fossils within the Genteng Formation indicates that its early deposition marked a transition from marine to terrestrial-type environments. These newly established terrestrial conditions created new habitats, particularly conducive for woody plant ecosystems. These ecosystems thrived due to optimal regional climatic conditions, fostering the ideal growth of woody plants and enhancing overall ecosystem productivity. Over time, these woody plants multiplied and transformed the landscape. Their natural preservation was facilitated by a combination of biological aspects and geological events that supported fossilization. As a result, the abundance of woody vegetation contributed to the success of wood fossilization over millions of years of geological processes.

The Significance of Wood Fossils from Jasinga. Dipterocarpaceae, the most abundant wood fossils found in this study, are widely distributed in tropical climates, particularly in Southeast Asia. This study has revealed genera that are now locally extinct in Java, including modern species like *Dryobalanops* and *Parashorea,* which can no longer be found even in natural forest conservation areas. Currently, the natural habitat of *Shorea javanica* is limited to remote rainforests in southern Java, such as the Leuweung Sancang Garut Nature Reserve (Mandang and Martono, 1996; Wakhidah et al., 2020), while *Vatica bantamensis* only occurs in Ujungkulon National Park (Robiansyah and Hamid, 2019). Other modern species of genera *Dryobalanops* and *Parashorea* are also exclusively found in remote natural forests in Sumatra and Kalimantan (Nutt et al., 2016; Harnelly et al., 2018; Ritonga et al., 2018). Recently, Dipterocarpaceae have a narrower distribution and are less abundant compared to other tropical trees.

The presence of dipterocarp wood fossils indicates the existence of stable primary paleoforest ecosystems. These trees can survive for hundreds of years and form dense forest canopies. Tree heights reach 80 meters, with roots stretching between 6 to 10 meters (Ghazoul, 2016). Dipterocarp forests thrive in ideal tropical climates, with temperatures ranging from 23°C to 28°C and an annual rainfall of 2000–3000 mm. They grow best in areas with a high level of direct sunlight. Trees from the Dipterocarpaceae group tend to grow in well-drained and nutrient-rich soils, including sandy, clayey, and loamy soils. Dipterocarp forests typically grow in valley areas, hillsides, and gentle-to-moderate slopes (less than 15 degrees). The Dipterocarpaceae species typically grow at low to mid-elevations, ranging from sea level to approximately 1500 meters above sea level (Susanty et al., 2013; Ghazoul, 2016; Morley, 2000). Dipterocarp forests are known for their high biodiversity. The dipterocarp forest floor is home to a diverse range of understory plants, including ferns, shrubs, and herbs. Additionally, these forests exhibit high levels of microbial diversity, including bacteria, fungi, and other microorganisms (Fuji, 2014). These microorganisms are important in nutrient cycling, soil formation, and other ecological processes. Dipterocarp forests can be sustained in undisturbed areas for over a thousand years. However, in some affected areas, tropical storms and geological hazards such as volcanoes may trigger the fall of dipterocarp trees (Brearley et al., 2016; Chechina and Hamann, 2019). The fallen wood logs can be suddenly buried and gradually fossilized during the rock diagenesis.

Besides dipterocarps, wood fossils in Jasinga can also be found in taxa that are analogous to the genera *Terminalia* (Combretaceae), *Alstonia* (Apocynaceae), *Dichrostachys* (Fabaceae), and *Ochanostachys* (Olacaceae). *Terminalia* and *Alstonia* are primarily found in tropical and subtropical regions of Asia, Africa, and Australia. Many *Alstonia* grow in tropical rainforests where they thrive in the understory or mid-story layers of the forest. These plants adapted to low light levels and high humidity (Marjenah and Putri, 2017; Baas et al., 2019). Some *Alstonia* species, such as *Alstonia scholaris*, are found in wetlands and swamps, where they have adapted to wet and marshy conditions. *Ochanostachys* have been found in tropical regions (Heriyanto et al., 2019). Many *Ochanostachys* species can be found in tropical rainforests, where they grow in the understory or mid-story layers of the forest. These plants have adapted to low light levels and high humidity (Su et al., 2015; Lee et al., 2019). Some *Ochanostachys* species are found in drier coastal habitats. These plants are adapted to seasonal rainfall patterns, often have thick, drought-resistant leaves, and are adapted to low salinity conditions. *Dichrostachys* are primarily found in Africa and Asia's tropical and subtropical regions. They grow in riparian zones, which are areas of land adjacent to rivers and other bodies of water. These plants have adapted to periodic flooding and have developed particular adaptations to survive in this environment (Pin et al., 2013; Randle et al., 2018).

The wood fossils in Jasinga consistently indicate the paleoenvironment of tropical rainforests. These woods typically grow in drainage ecosystems that receive intense sunlight and are associated with riparian areas, such as rivers, marshes, or swamps. The paleotopography of the area likely varied, with hills and valleys providing relatively thick soils for deeper dipterocarp root zones. This allowed trees to grow taller and form dense forest canopies. The study results showed a higher diversity of wood fossils in the Middle Sandstone rock unit. Here, the facies represent a hilly mixed dipterocarp forest in the presence of *Dipterocarpoxylon*, *Dryobalanoxylon*, *Parashoreoxylon*, and *Terminalioxylon* wood fossils. The fossilized palynomorph in this facies also indicates a variety of paleoforest floor plants.

Palynomorph Fossils Evidences. Fossilized palynomorphs from this study indicate the existence of a more diverse paleovegetation, in addition to being based on wood fossil taxa. They also reveal the ecosystem's productivity in the paleotropical forest, where these vegetations actively grow, reproduce, and distribute. Pollen and spore fossils also reflect the seasonal paleoclimate, which is ideal for the flowering and reproduction of these paleovegetations, similar to modern Dipterocarpaceae and Convolvulaceae. Other palynomorph fossils originate from forest floor paleovegetation, representing humid and shaded paleohabitats. Additionally, *Florschuetzia* and *Stenochlaenidites* are often associated with lowlands and coastal paleoenvironments.

Wood Silicification. The results show that the collected wood fossil samples were almost entirely silicified; this is indicated by the XRF results, with 92.7 ± 1.88% w/w of wood fossil composed of silica oxide. The carbon features of wood no longer dominate based on the appearance and hardness of wood fossils. Thin-section observations revealed the presence of quartz, opal, and chalcedony crystals filling the pores of wood fossil bodies, particularly in vessels. Interestingly, these processes did not extensively damage the wood tissue structure. From a cross-sectional view, the wood tissue structure remains clear and morphologically distinguishable, although some minor structures are no longer visible due to crystallization. Silicification appears to fill the porous parts before further crystallization; this seems to be related to the role of soluble silica, such as H_4SiO_4 ($H^+ + H_3SiO_4^-$), which dissolves from the surrounding host rock (Mustoe, 2017). In the lithostratigraphy, there are several silica-rich tuffaceous beds. Gradually, this soluble silica infiltrates the wood tissue, undergoes silica permineralization, and finally replaces the organic structure with silica-based material. These silicas gradually replace carbon, upholding the structure and preserving the shapes of wood tissues along with the geological process. Other minerals, such as hematite (iron oxide), are also involved in wood fossil coloring. This condition is closely related to the paleoenvironment during wood fossilization (Mustoe, 2023), which determines the characteristics of the paleodepositional environment during permineralization, especially in silicification.

Paleoenvironmental Setting of Jasinga. The rock units in the lithostratigraphy of Jasinga, West Java, demonstrate facies changes during the deposition of the Genteng Formation since the Early Pliocene (Table 2). It began with fast-flowing deposition conditions with volcanic provenances consisting of andesitic-volcanoclastic rocks and a small number of siliciclastic. This deposition gradually initiated the transition from a marine environment during the Late Miocene to a terrestrial environment. As the terrestrial environment expanded, fluvial systems were concurrently established, and woody vegetation, such as *Anisopteroxylon* and *Alstonioxylon*, also began to be introduced naturally and grew, characterizing a lowland near-shore dry forest. This ecosystem gradually formed along the shore before being buried by lahar flows resulting from near-paleovolcanic activity, which delivered the fluvial-volcanoclastic material into surrounding depositional environments. However, the lahar mass flows triggered new landmasses, and the terrestrial environment expanded, accompanied by fluvial complexity that triggered the formation of habitats for various vegetation, including the dipterocarp group. Dipterocarp forests require decades to hundreds of years to develop and sustain.

TABLE 2. Presence of fossil taxa in rock facies units in the study area (✓: present) and their related paleoenvironment.

Family	Wood fossil genus	Older ---------- Lithostratographical rock unit --------- Younger					
		Lower conglomeratic facies	Lower sandstone facies	Breccia laharic facies	Middle sandstone facies	Upper conglomeratic facies	Upper siltstone facies
Dipterocarpaceae	*Anisopteroxylon*	-	-	✓	-	✓	-
Dipterocarpaceae	*Dipterocarpoxylon*	-	-	-	✓	-	-
Dipterocarpaceae	*Dryobalanoxylon*	-	-	-	✓	✓	-
Dipterocarpaceae	*Parashoreoxylon*	-	-	-	✓	✓	-
Dipterocarpaceae	*Shoreoxylon*	-	-	-	-	-	✓
Apocynaceae	*Alstonioxylon*	-	-	✓	-	-	-
Combretaceae	*Terminalioxylon*	-	-	-	✓	-	-
Olacaceae	*Ochanostachixylon*	-	-	-	-	-	✓
Fabaceae	*Dichrostachixylon*	-	-	-	-	-	✓
Type of paleoforest based on the occurrences of wood fossil		-	-	Lowland nearshore dry forest	Hilly mixed dipterocarp forest	Hilly to lowland mixed dipterocarp forest	Mixed deciduous forest
Paleo-depositional environment		Transitional area	Low energy fluvial area	Lahar channel valley area	Low energy fluvial area	High energy fluvial area	Low energy fluvial-marshy area

Additionally, they require a tropical climate to thrive under ideal primary conditions. The findings of fossil wood variations from different dipterocarp groups indicate several episodes where paleoecology was slightly disturbed. Although natural disturbances such as tropical storms or volcanic eruptions occurred, some parts of the forest survived, maintaining the gene pool of dipterocarps in that area. Dipterocarp trees such as *Dipterocarpoxylon*, *Dryobalanoxylon*, and *Parashoreoxylon*, and non-dipterocarps like *Terminalioxylon*, appeared simultaneously during the deposition of the Middle Sandstone rock unit, characterizing a hilly mixed dipterocarp paleoforest with paleodeposition in a low-energy fluvial area. In this episode, non-arboreal vegetation covering the forest floor can also be found, such as flowering plants of Convolvulaceae and *Florschuetzia*, as well as ferns from *Stenochlaenidites*, *Verrucatosporites*, and *Lygodium* palms. In the subsequent episode, the orogenic process continued, leading to hilly conditions and the formation of steep drainage systems with various dipterocarps such as *Anisopteroxylon*, *Dryobalanoxylon*, and *Parashoreoxylon*, characterizing a hilly to lowland mixed dipterocarp paleoforest with paleodeposition in a high-energy fluvial area, possibly related to an alluvial fan environment. The presence of the Upper Conglomeratic rock unit indicated this condition. Hilly conditions increase the potential for flash floods that could quickly bury wood in the surrounding area and preserve it for atmospheric decomposition. In the younger episode, the forest tended to become more open and a swampy environment with mixed vegetation dominated by *Shoreoxylon*, *Ochanostachysoxylon*, and *Dichrostachyoxylon*, representing a flat topography with mature geomorphological characteristics associated with a low-energy fluvial-marshy area.

The lithostratigraphy of Jasinga also demonstrates that fluvial-volcaniclastic deposits, such as tuffaceous beds, can be found in almost every rock facies. The presence of tuff suggests nearby paleovolcanic activities, including laharic breccia facies in older strata. Volcanic deposits, such as tuff and lahar, have a high silica content, which can be leached due to weathering activity on the surface. Infiltrated water flow appears to carry soluble silica and fills the pores of the buried wood logs. Some trees may have fallen, deposited, and buried along with the silica-rich sediments. Catastrophic events, such as massive volcanic ashfall and lahar flows, instantly topple trees nearby. These events suddenly bury the wood and prevent natural decomposition due to humid conditions, chemical degradation, or organic decomposition activities from detritus and microorganisms.

Geographically, the study area represents the southern part of Sundaland. Several researchers have studied the paleogeography of this region. During the Late Miocene to Early Pliocene, the paleogeography of the south part of Sundaland was dominated by marine environments. Many studies have reported marine mollusk fossils and carbonate rock formation during this period (Aswan et al., 2013; Berghuis et al., 2019; Harbowo et al., 2023). Morley et al. (2016) also demonstrated the paleogeographic reconstruction of Southeast Asia during the Late Miocene to Early Pliocene using comprehensive sediment core data. Subduction of the Indo-Australian tectonic plate in the southern part of Sundaland formed the volcanic arc in this region since the Pliocene. Pliocene volcanoes intensively produced volcanic materials that gradually formed new islands, and the landmasses expanded over time. Uplifting tectonic events shaped various geomorphologies, including hills and lowlands. Soil formation continued in the landscape along with the Pliocene tropical climates. We suspect that the seed pool of plants in this area comes from the nearest mainland to the north, such as Sumatra. Some pioneer vegetation likely grew in this area, possibly carried by water or pollinators like coastal birds. By then, much land had formed in southern Sumatra, some of which had been covered by woody plant species since the Cretaceous (Harbowo et al., 2022; Morley, 1998). At a more mature stage, seeds from higher-level vegetation, including Dipterocarpaceae, were introduced and gradually grew in this area, forming an established more complex dipterocarp forest. Although Pliocene volcanic activity occurred in these regions, it did not destroy the habitat majorly. Some areas survived and played a role in natural succession. However, at the end of the Pliocene, the cooler climate has influenced the selection of Dipterocarpaceae in this region, particularly during glacial periods in the Pleistocene.

This study has uncovered several aspects of natural history in the region. However, much remains to be explored, especially in understanding the changes in paleoclimate conditions from tropical to glacial. Additionally, there is a need to investigate paleoecological productivity and specific paleo-depositional settings that led to natural wood silicification for further study. Nonetheless, this study has provided a helpful starting point for conservation efforts. It can serve as a guide for conserving wood fossils in the region, enhancing the management of these valuable resources. Understanding the scientific value of wood fossils can help comprehend a region’s geological history, climate dynamics, environmental changes, and evolution, particularly for developing models and predicting future climatic and environmental changes. Improving the management of wood fossil resources while maintaining their scientific value could involve requiring collectors to record detailed information about discovered wood fossils and submitting the data to local governments and researchers before selling them. Initiatives should be taken to restore dipterocarp forests in the area based on paleoecological considerations and the characteristics of existing taxa. Establishing conservation areas in similar regions to preserve wood fossils is also necessary. Further research will contribute to best practices for sustainable environmental management.

CONCLUSIONS

Various wood fossils of Dipterocarpaceae have been found in Jasinga, West Java, including *Anisopteroxylon*, *Dipterocarpoxylon*, *Dryobalanoxylon*, *Parashoreoxylon*, and *Shoreoxylon*. Several non-dipterocarp wood fossils were also discovered, including Apocynaceae (*Alstonioxylon*), Combretaceae (*Terminalioxylon*), Olacaceae (*Ochanostachysoxylon*), and Fabaceae (*Dichrostachyoxylon*). Fossilized palynomorphs of varying types were also recovered and identified, including pollen types from Dipterocarpaceae, Convolvulaceae, and *Florschuetzia*, as well as spore types from *Stenochlaenidites*, *Verrucatosporites*, and *Lygodium*. These paleontological evidences indicate the existence of paleoenvironmental episodes of paleotropical rainforests in the southern part of Sundaland since the Early Pliocene. Most rock facies in this area are associated with fluvial-paleovolcanic deposits, represented by the discovery of silica-rich facies as tuffaceous beds and lahar breccia deposits in the rock strata. These deposits are also responsible for wood fossilization, primarily through silicification. Further conservation efforts are essential for enriching their scientific value.

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