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A diverse assemblage of fossil hardwood from the Upper Tertiary (Miocene?) of the Arauco Peninsula, Chile

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Abstract

Silicified woods of 10 dicotyledonous tree families of probably Miocene age from the Arauco Peninsula, central Chile are described and classified according to their anatomy. The diversity is surprisingly high, in that of the 19 samples analyzed, virtually every one could belong to a different species of tree or shrub. Almost all species document a damp climate, and most have related species living in the central zone of modern Chile. The samples were collected in a narrow zone on Punta El Fraile, west of the town of Arauco. The following families are based on woods from the Arauco Peninsula: Anacardiaceae, Boraginaceae, Euphorbiaceae, Fagaceae, Lauraceae, Leguminosae, Monimiaceae, the first report of fossil Myristicaceae, Myrtaceae, and Proteaceae. Their diagenetic history is connected to tuffaceous material and calcareous concretions.

Keywords: Angiosperms; Arauco Peninsula; Chile; Fossil wood; Miocene; Wood anatomy

1. Introduction

Pebbles consisting of silicified fossil wood were encountered along the beach of the northern Arauco Peninsula, Chile. Nineteen samples were collected at Punta El Fraile (Fig. 1, ca. 37°12′S, 73°29′W), a few kilometers west of the village Tubul. The woods are originally from a layer exposed in an outcrop of clay- and siltstones (Fig. 2). The fauna in these claystones is of marine origin and consists mainly of molluscs, sea urchins, and crustaceans. The outcrop belongs to the Late Miocene, probably of Tortonian age (Finger et al., 2003). An analysis of the fossilized woods reveals an astounding variety of trees and bushes that may represent tree-like dicotyledonous angiosperms of 10 different families. Both the numerical diversity of the types of trees that formed the fossil woods and the absence of conifers were unexpected. Tertiary petrified plants in Chile and Argentina have been well documented (e.g. Kräusel, 1925; Salard, 1961; Archangelsky et al., 1969; Palma Heldt, 1978; Ragonese, 1980; Nishida et al., 1987; Taylor, 1991), but fossil woods and angiosperms of central Chile have been described only by a few authors (e.g. Nishida, 1984a,b; Nishida et al., 1988, 1990).

Because the diversity is so high, more analyzed wood from that locality probably would lead to even more diversity. This article gives an overall comparison with extant woods, and a comparison with other fossil woods is in preparation. The surrounding sediment indicates that (1) wood silicification occurred under the influence of tuffaceous material and the formation of carbonate concretions; (2) silicified wood, which is resistant to erosion, was transported over long distances; and (3) pebble transport along the shore occurred from west to east.

2. Geological setting

The basement in the Arauco Peninsula and Concepción (to the north) consists of metamorphic Paleozoic sedimentary rocks intruded by igneous bodies. These rocks are exposed near Concepción at Penco and Quiriquina Island. The marine sediments of the Late Cretaceous Quiriquina Formation contain a diverse marine fauna (Stinnesbeck, 1986; Bandel and Stinnesbeck, 2000), separated from sandstones of fluviatile to coastal origin of the Paleogene by a more or less clear unconformity. This transition is well exposed on Quiriquina Island and in the Schwager coal mine at Coronel.

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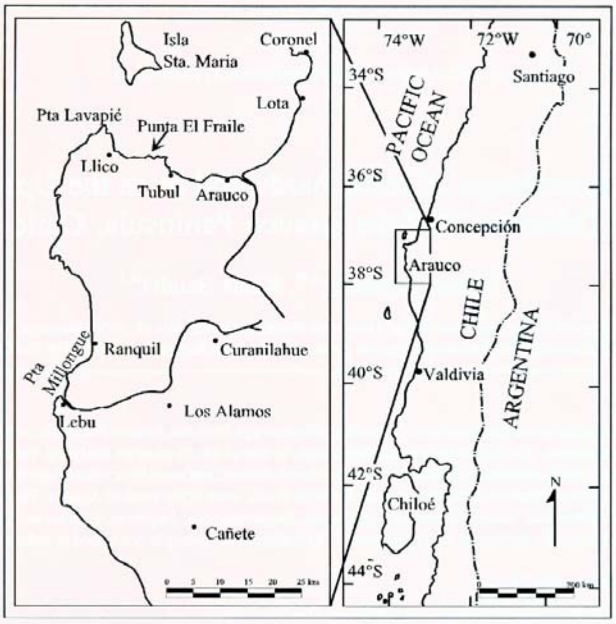

Fig. 1. Location map with place of discovery (modified according to Nielsen and De Vries, 2002): central Chile (right) and the Arauco Peninsula (left). The 19 woods were collected at the beach at Punta El Fraile (left, indicated by arrow).

The stratigraphy and depositional history of the coal-bearing Paleogene deposits of Arauco Peninsula, Coronel, and Lota have attracted much attention (e.g. Brüggen, 1934; Tavera, 1942; Muñoz Christi, 1946; Zeil, 1964; García, 1968; Wenzel, 1982; Pineda, 1986; Le Roux and Elgueta, 1997). According to these authors, the base of the coal-bearing deposits may reach into the Paleocene. The depositional environment is thought to have changed locally and temporally from shallow marine to coastal continental and is estimated to be of Eocene age. It is also suggested that the deposits of the Arauco Peninsula are formed at their base by the Curanilahue unit, which is 50 to a few hundred meters thick and composed of intercalated marine and continental deposits and some coal seams. Above it is emplaced the Boca Lebu unit, which is more than 500 m thick in some places and composed mainly of sandstones formed in a marine environment. The Boca Lebu unit is overlain by up to 550 m of sediment of the Milliongue unit, composed of marine sandstones and tuff. This unit is intercalated to the east with the Trihueco unit, 180 m of limnic and continental sediments, including coal seams.

Coastal swamp deposits were intercalated with marine sandy deposits during the Eocene. Coal is believed to have formed behind sandbars near the shore of the Pacific Ocean. According to Palma Heldt (1978), the coal of the Lota member of the Curanilahue unit contains spores and pollen of approximately 10 species of ferns, four species of conifers (including Podocarpacea and Araucariacea), and 10 species of dicotylous and two of monocotylous plants. According to her interpretation, a wet subtropical climate prevailed in the Eocene along the shores of Arauco and Concepción. Tavera (1942) notes numerous species of gastropods and bivalves in Lebu, concentrated in layers within the sandstones of the Eocene. Some of these are described by Philippi (1887) and others by Tavera (1942); all are relatively badly preserved but represent approximately 20 species of bivalves and 30 species of gastropods.

Oligocene sediments are unknown from the Arauco Peninsula. According to Zeil (1964), during the Oligocene, Eocene deposits—up to 1400 m thick—were indurated and deformed before Miocene sediments of the equivalent of the marine Navidad Formation were unconformably deposited on them. The Eocene sandstones near Lebu, at the southern tip of Arauco Peninsula, have been diagenetically altered to such an extent that they formed rocky cliffs, which were eroded by the sea during the Miocene. In addition to shells of molluscs and other invertebrate remains that lived in the wave-washed rocky cliffs, the crevice fillings also contain coal pebbles. Diagenesis thus affected the Eocene sediments so much that coal became hard enough to be eroded into pebbles.

The Miocene Ranquil Formation overlies the sandstones of the Eocene with a more or less well-expressed

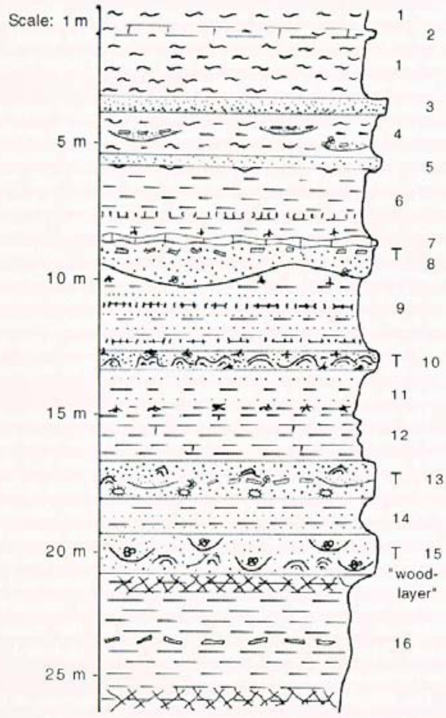

Fig. 2. Stratigraphic log of the outcrop in which the fossil woods were originally found (wood layer). Sketch of the section exposed on the beach between Punta El Fraile and the bay near Llico (see Section 2). T, unit with tuffitic material. (1) Bioturbated marly claystones, locally with more calcareous cement (2). (3) Graded, bedded sandstones with cross-bedding. (4) Bioturbated marly claystones with channel sand fills containing clay clasts and coaly wood fragments. (5) Bioturbated sandstone with erosional base; burrows. (6) Interbedded clay- and siltstones with a base of limestone; single bioturbated layers, burrows. (7) Bioturbated marly claystones. (T8) Sandstone with channel sand fills, volcanic clasts, and clay chards at the top; wood fragments in channel sand fills at the base of the unit. (9) Laminated clay- and siltstones with less bioturbated single layers. (T10) Sandstone with tuffitic material; convoluted structures. (11) Laminated clay- and siltstones; burrows in single layers; bedding planes with wood fragments. (12) Bioturbated calcareous sediments with concretions. (T13) Sandstone with tuffitic material and mud chards; convoluted structures; layers with ripple-marks and trace fossils; channel sand fills with wood fragments. (14) Laminated clay- and siltstones. (T15) Wood layer of sandstone with channel sand fills; mud shards in upper layers of channel fills; channel/beach sand fills with volcanic material (partial with obsidian), calcareous components with concretions, convolute structures, erosion pits, shell and wood fragments. (16) Claystones with irregularly eroding structures (root horizon) at the top; sandstone layers with ripple marks; mud shards.

unconformity. This Formation is time equivalent to the better known Navidad Formation (Finger et al., 2003), with its type locality on the Pacific coast near Santiago de Chile. The Miocene is well exposed on the Arauco Peninsula at Punta El Fraile near Tubul, to the south near Ranquil, and near Lebu. Several types of rock facies occur in these deposits, documenting sedimentation on and near the rocky shore, near and behind quiet beaches, and on the open shelf, probably at a depth of >1500 m. However, a complex history of reworking and mixing of sediments of different ages during the Late Miocene occurs in the contemporaneous Navidad Formation (Encinas et al., 2003; Nielsen et al., 2003) and has been inferred for the Ranquil Formation (Finger et al., 2003). The Ranquil Formation of the Arauco Peninsula consists of two facies types, one dominated by sandstone and the other by gray siltstone and clays (see Nielsen et al., 2004). The thickness of the sediment is not well known because many silty and clay-rich portions of the deposits have been misinterpreted as belonging to the Eocene sedimentary sequence or representing younger deposits (Boettcher, 1999, fig. 6). However, up to 400 m of sediment belonging to the Miocene may be locally present. At Ranquil, approximately 7 km north of Lebu, the cliffs expose sediments that suggest a complex depositional history of the Ranquil Formation. Fine-grained silt- and claystones with a rich fauna of open-shelf environment have been uplifted to form coastal cliffs, which were subsequently eroded, slumped, and later covered by marine sands, which also bear a shallow marine environment fauna.

Mpodozis and Ramos (1989) describe an active chain of volcanoes in the more continental area to the east, with rocks forming the Ventana Formation south of Temuco. Volcanism east of the Arauco Peninsula is indicated during the deposition of Ranquil Formation by intercalations of tuff-bearing beds with layers containing volcanic glass at Ranquil, as well as at the northern beach, between Punta El Fraile and the bay next to Llico.

The beds of the Miocene Ranquil Formation are unconformably overlain by Pliocene marine beds of the Tubul Formation, which are up to 300 m thick. According to Martínez (1976), the sediments of the Tubul Formation were deposited during the Late Pliocene. The unconformable contact is well exposed near the village of Tubul. The marine beds were since raised above sea level and form conspicuous cliffs between Arauco and Tubul. Sandstones of the Tubul Formation subsequently have been caved, and their eroded surfaces are overlain in many places by Holocene deposits formed after the last flooding, which was due to postglacial sea level rise.

The layer containing wood (Fig. 2) is included in a series of up to 150 cm of cross-bedded channel sands, some of which contain coarser, tuffaceous sediments. Good exposure begins in the small bay west of the cemetery near Punta El Fraile and ends shortly before Llico. Fig. 2 illustrates the transition from fully marine marls to the wood-bearing layer 20 m below (T15). Below the bed containing silicified wood are 50 m of additional layers before the oldest deposits of the anticline are reached. Between the cemetery and the beginning of the section, the exposed marly claystones exhibit a marine molluscan fauna similar to that of Punta El Fraile. The measured section begins west of this settlement with a marly claystone unit (1) that contains layers with more calcareous cement (2). This sediment is thoroughly bioturbated. A sandy, graded bed with cross-bedding preserved at the base of the unit (3) indicates a change in deposition and approaching near-shore conditions. It is mostly bioturbated, as is the next marly claystone unit (4), which includes up to 2 m wide, 10 cm deep, sand-filled channels. Clay clasts and soft coaly wood fragments also are present in this layer. A sandy bed follows (5), bioturbated from above by one type of vertical, nonbranching burrow. Its base was formed by erosion, which left groove marks and sudden changes in grain size. The layers below consist of intercalated clay- and siltstone (6), within which bioturbation is restricted to single layers and uniform types of burrows. Some layers feature vertical burrows as well as larger, branching crab burrows. A 30-cm thick bank of limestone forms the base for this unit, which tops a thoroughly bioturbated, marly claystone unit (7). The bed below features the influence of shore conditions and consists predominantly of sand-filled channels (T8). In this unit, coarser sand holds volcanic clasts; tuffitic influence is indicated by greenish coarse sand. In the deepest portion of the channels, wood fragments are common; in the top layers, clay shards appear. The laminated layers below consist of clay and siltstone (9), which are neither bioturbated nor penetrated by vertical burrows in dense patterns but contain a few bioturbated, concentrated, single layers inside. The following bed composed of tuffitic coarse sand (T10) was deposited rapidly, and therefore, dewatering structures formed in large convoluted structures. The beds below are well laminated (11) and have burrows only in single layers. Bedding planes show plant fragments with soft and coaly wood particles. Concretions formed in the more calcareous sediments below (12), and bioturbation destroyed much of the original sedimentary structures. A coarse-grained sandstone unit, more than 1 m thick, follows (T13). This unit contains tuffitic material and layers with convoluted structures or channel fills. Rippled surfaces are seen, as well as surfaces showing trace fossils that display activities of irregular sea urchins. Coaly driftwood fragments are common. Near-shore conditions are documented by layers of mud shards. Below this coarse bed are laminated silt- and claystones (14).

The next lower unit, approximately 1.5 m thick, represents the bed from which the silicified wood originates (T15). It is composed of channel or beach sands, into which depressions filled by coarser material have been eroded. These may have represented erosion pits into the channel or beach sands that were filled with driftwood, shell fragments, and volcanic debris. The calcareous components of the channel filling resulted in the formation of concretions that may contain wood. Clay balls, mud clasts, and shards are present in the upper layers of channel fills, indicating their position in an intertidal or even supratidal environment. Finer channel sand holds convoluted structures, indicating rapid deposition. The volcanic material consists mostly of fine- to sand-grained material but also includes larger bombs of black volcanic glass (obsidian).

Below this channel sand, a claystone unit of approximately 5 m is exposed (16). Because of irregularly eroding expressions at the top, the layers indicate root horizons. Sandy layers with rippled surfaces and layers with mud shards are also present, indicating a deposition behind a beach in a coastal area that was periodically flooded. The layers below consist of similar sediment. Approximately 15 m of clay and siltstones are exposed, into which single channels filled with sand have been eroded. The base of the section is formed by 8 m of predominantly sandy channel fills with a soil-clay intercalation. With this layer, the top part of the anticline is reached. The sequence repeats to the west in the direction of Llico.

The wood pieces found in layer T15 are predominantly well rounded. Their size ranges from short trunks, more than half a meter in diameter, to small twig fragments less than 1 cm in diameter. Most wood pieces have not been drilled, but some contain teredinid tubes. In the latter case, the wood is abundantly riddled by tubes, which have been coated by calcitic deposits. However, more than 95% of the wood is of fresh appearance, commonly rounded and not penetrated by marine woodboring organisms. In shape it resembles driftwood, which is locally deposited on the modern beach. Many of the pieces have been included in concretions of calcium carbonate.

The silicified woods at their location of exposure at the beach level migrated east along the beach, toward Punta El Fraile. Following the exposed sequence along the beach to the west, the top of the anticline is reached, with its western flank exposed on the way to the bay adjacent to the village of Llico. At this location, the beds dip gently west and toward the Bay of Arauco to the north. The layer containing silicified woods is also exposed on the western side of the anticline but not as conspicuously as on its eastern side. However, its occurrence is well documented by the silicified woods found on the beach close to the outcrop of the sandy and tuffaceous layers that contain it.

3. Materials and methods

Nineteen beach-washed, rounded pieces of silicified fossil hardwood, collected at the northern shore of the Arauco Peninsula (ca. 37°12′S, 73°29′W) at Punta El Fraile (Fig. 1), a few kilometers west of Tubul, were analyzed. Most are well preserved with a visible main tangential wood structure on the surface (Plate 1 [3, 4]). Transverse, tangential, and radial thin sections were prepared to observe and describe the structure of the woods (Plate 1 [3]). The identification of the wood anatomy was based on the Richter and Dallwitz (2000), Dallwitz (1980), Dallwitz et al. (1993, 1995), and Watson and Dallwitz (1991, 1992), wood databases, and the IAWA

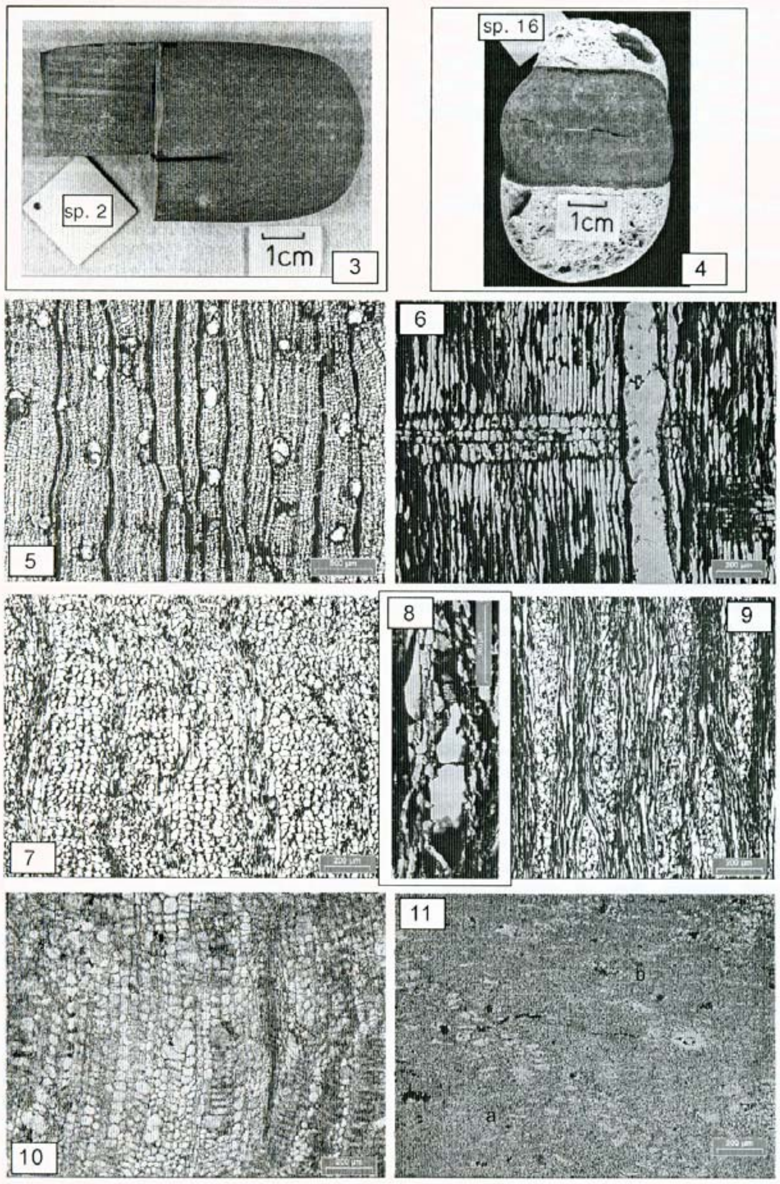

Plate 1. (3 and 4) Wood samples, (3) visible wood structure on the sample surface; three-dimensional sections were prepared to describe the wood anatomy; (4) wood within volcanoclastic sediment. (5 and 6) Anacardiaceae, (5) transverse section of specimen 12, scale bar 500 μm; (6) radial section of specimen 12, scale bar 200 μm. (7–9) Boraginaceae, (7) transverse section of specimen 11, scale bar 200 μm; (8) radial section of specimen 11, tangential vessel diameter is approximately 200 μm, scale bar 200 μm; (9) tangential section of specimen 11, rays with sheath cells, scale bar 200 μm. (10) Euphorbiaceae, transverse section of specimen 17, scale bar 200 μm. (11) Fagaceae, transverse section of specimen 18, [a] earlywood, [b] vessels of latewood arranged in dendritic patterns, scale bar 200 μm.

list of features suitable for hardwood identification (IAWA Committee, 1989). Subsequently, comparisons with extant wood samples were made in the Federal Research Centre for Forestry and Forest Products, Hamburg, Germany. The fossil woods are deposited at the Mineralogisch-Petrographisches Institut, University of Hamburg, Germany.

4. Description and identification of the wood anatomy

4.1. Anacardiaceae

Three pieces of fossil wood (specimens 6, 12, and 16) can be attributed to the Anacardiaceae. Among them, specimen 12 (Plate 1 [5, 6]) is preserved as black silicified wood. Through transmitted light, the material is gray to black, and the organic material is orange brown to reddish brown. The other two specimens resemble specimen 12 in look and preservation.

The wood is diffuse porous. Vessels are distributed in no specific pattern or in multiples, commonly in short (1–2 vessels) radial rows (Plate 1 [5]). Perforation plates are simple. Intervessel pits alternate and have an average pit diameter (vertical) of >10 μm. Extremely large ray pits with strongly reduced borders or simple rounded or elongated shape appear. The fibers are arranged in radial patterns seen in the transverse section (Plate 1 [5]). Axial parenchyma is paratracheal and vasicentric. Rays are uni- or multiseriate, 2–3 cells wide. Rays are heterocellular and composed of two or more cell types (Plate 1 [6]).

The wood of specimen 12 displays the characteristics of the family Anacardiaceae, such as coarse and heterocellular wood fibers, alternating and large intervessel pits, and radially arranged fibers. The other two specimens (6 and 16) are similar in the wood anatomy but vary with regard to the quantity of vessels and rays. All three woods are different, but in the basal anatomy, they are representatives of Anacardiaceae.

4.2. Boraginaceae

Only specimen 11 (Plate 1 [7–9]) belongs to the Boraginaceae. The silicified wood is gray to dark gray with cracks filled with white material. Through transmitted light, the material is reddish brown to black, and the organic material is orange. It is probably a wood of burl because, in addition to the wavy and bended wood structure, all three sections (transverse, tangential, radial) are seen in one plane.

The wood is diffuse porous. Vessels are distributed in no specific pattern, and the average tangential vessel diameter is 120 to >200 μm (Plate 1 [8]). The diameter of the vessel lumina is large. Perforation plates are simple. Intervessel pits alternate, and their average diameter (vertical) is small (4–5 μm). Vessel ray pits have reduced borders or appear simple. Axial parenchyma is present, apotracheal, and paratracheal, and the parenchyma bands appear marginal. Apotracheal axial parenchyma is in diffuse aggregates. Rays are sometimes multiseriate, 3–5 cells wide (Plate 1 [7]), and larger rays are of medium width with heights up to 2000 μm. Sheath cells are present (Plate 1 [9]).

The combination of the described features for this wood is known from the genus *Cordia* of the Boraginaceae.

4.3. Euphorbiaceae

Only specimen 17 (Plate 1 [10]) belongs to the Euphorbiaceae. The preserved sample contains brown silicified wood in its matrix. The specimen documents, by its shape in the sediment, that it was rounded driftwood. In transmitted light, the material appears brown; at higher magnification, the organic material appears brown or gray.

The wood is diffuse porous. Vessels are distributed in no specific pattern, in multiples, and commonly in short (2–3 vessels) radial rows or radial rows of four or more (Plate 1 [10]). The average tangential vessel diameter reaches >200 μm. Intervessel pits alternate. The axial parenchyma is present and diffuse. Rays are arranged exclusively uniseriate and composed of two or more cell types (heterocellular).

The combination of radially arranged rows of vessels consisting of four and more cells and large alternating pits with rays only in single rows indicate that the wood belongs to a representative of the Euphorbiaceae. The character of the fossil wood resembles that found in the genus *Sapium*, but other genera of this family are similar.

4.4. Fagaceae

Two specimens may be placed in the Fagaceae (18 and 19). Among these, specimen 18 (Plate 1 [11]) shows the same preservation as specimen 17.

The wood of specimen 18 appears semi-ring porous and diffuse porous. Vessels are arranged in dendritic patterns (latewood) (Plate 1 [11a, b]). Intervessel pits alternate. Vessel ray pits appear simple or angular. Tyloses are present in early wood. Rays are uni- or multiseriate.

The wood of specimen 18 is characterized by the dendritic orientation of the vessels in the latewood. The indicated ring-porous pattern, in connection with the inclined radial and dendritic vessel arrangement of the latewood, as well as tyloses in the large vessels of the early wood and the narrow wood rays, indicate that specimen 18 represents the Fagaceae (e.g. *Castanea*, *Castanopsis*, *Lithocarpus*) and, to a lesser extent, the Sapotaceae (e.g. *Bumelia*, *Sideroxylon*) or Rhamnaceae. The preservation is not good enough to decide conclusively.

Specimen 19 (Plate 2 [12–14]) contains brown silicified wood, which has been drilled by teredinid bivalves (Plate 2 [13]). Through transmitted light, the material appears brown

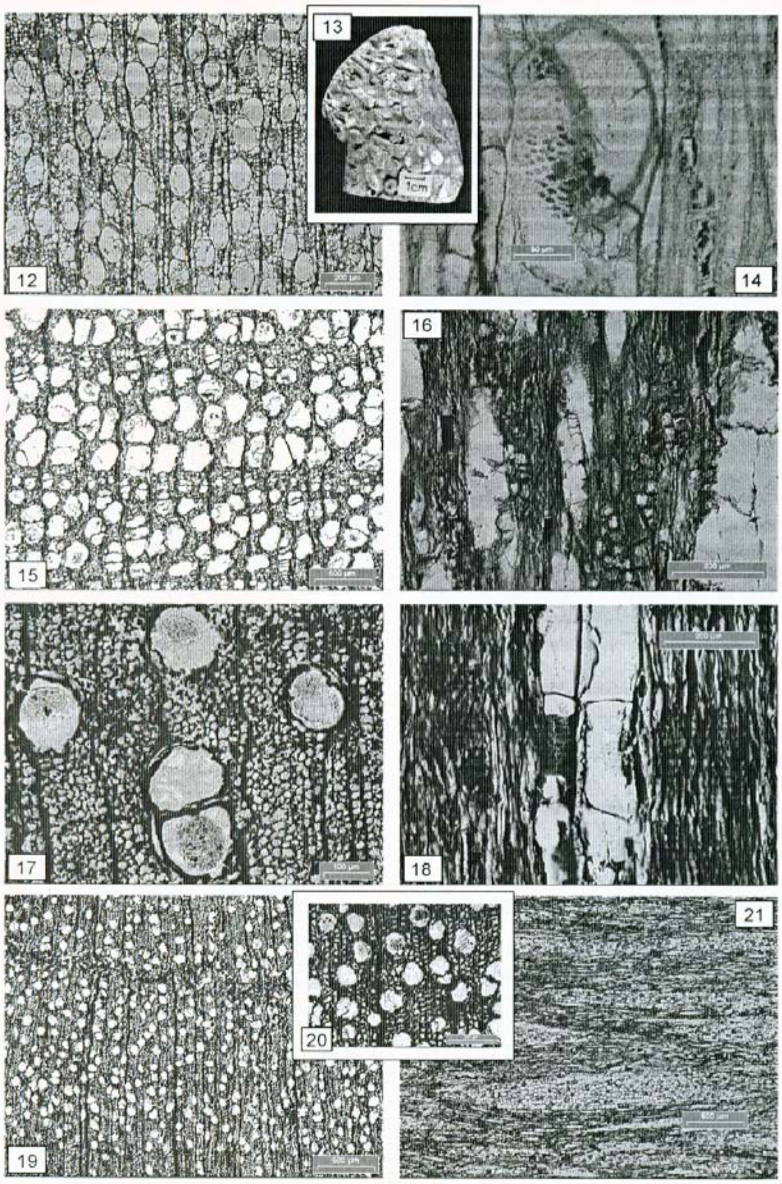

Plate 2. (12–14) Fagaceae, (12) transverse section of specimen 19, scale bar 200 μm; (13) specimen 19 drilled by teredinid bivalves, scale bar 1 cm; (14) tangential section of specimen 19, alternate intervessel pits, scale bar 50 μm. (15 and 16) Lauraceae, (15) transverse section of specimen 9, scale bar 500 μm; (16) tangential section of specimen 9, scalariform perforation plates in latewood vessels, scale bar 200 μm. (17 and 18) Leguminosae, (17) transverse section of specimen 5, scale bar 200 μm; (18) radial section of specimen 5, simple perforation plates in vessels, scale bar 200 μm. (19–21) Monimiaceae, (19) transverse section of specimen 2, scale bar 500 μm; (20) transverse section of specimen 2, scale bar 200 μm; (21) tangential section of specimen 14, scale bar 500 μm.

to light brown, and at higher magnification, the organic material is orange brown.

The wood appears diffuse porous. Vessels are distributed in no specific pattern, both solitary and in multiples (Plate 1 [12]). The average tangential vessel diameter is >200 μm, and the diameter of vessel lumina is large (ca. 100 μm; Plate 1 [14]). Intervessel pits are arranged opposite and alternate and have an average diameter (vertical) of >10 μm (Plate 1 [14]). Tyloses are present in the vessels. Regarding tracheids and fibers, vascular or vasicentric tracheids are present. The rays are uni- or multiseriate and heterocellular.

The medium-sized oval vessels, tyloses, and predominant alternate pits, combined with narrow uniserial wood rays and the presence of vascular tracheids, indicate that the wood belongs to a member of the family Fagaceae. Because of its cellular features, this wood is assigned to genus *Nothofagus*.

4.5. *Lauraceae*

Only specimen 9 (Plate 2 [15, 16]) belongs to the family Lauraceae. The silicified wood, with part of the bark preserved, is predominantly gray to black. Through transmitted light, the material appears brownish-gray to black, and the rays are dark brown. At higher magnification, the organic material appears orange brown.

The wood is ring porous to semi-ring porous (Plate 2 [15]). Vessels are arranged in multiples, commonly in short (2–3 vessels) radial rows and clusters (latewood) (Plate 2 [15]). Perforation plates are simple and scalariform (Plate 2 [16]). Intervessel pits alternate and have an average diameter (vertical) of >10 μm. Vessel ray pits are scalariform. Tyloses in vessels are probably present. The rays are multiseriate, 1–3 cells wide (Plate 2 [16]). Growth ring boundaries are distinct.

The vessels of the latewood are radially oriented, and the pits are arranged in scalariform manner. According to Carlquist (1980, 1988), specimen 9 represents type 9 of his classification of growth rings. Therefore, this could be a relative of *Pistacia* (family Anacardiaceae) or a member of Lauraceae. The general assembly of the elements of the xylem suggests the only ring-pore representative of Lauraceae, genus *Sassafras* (Richter, 1981), in which large alternating pits and scalariform vessel ray pits of the latewood occur (Richter, 1981; Carlquist, 1988; Poole et al., 2000). However, oil vesicles, which are diagnostic elements in the wood of modern *Sassafras*, have not been noted in the fossil wood of specimen 9.

4.6. *Leguminosae*

Only specimen 5 (Plate 2 [17, 18]) can be placed in the Leguminosae. This specimen is gray to black in color and transected by filled white cracks. Through transmitted light, the material is gray to black, and the rays are black. At higher magnification, the organic material appears reddish orange to reddish brown.

The wood is diffuse porous. Vessels are distributed in no specific pattern or in multiples, commonly forming short (1–2 vessels) radial rows (Plate 2 [17]). The average cross-section vessel diameter is >100 μm (Plate 2 [17]), and the average tangential vessel diameter is >200 μm (Plate 2 [18]). Perforation plates are simple (Plate 2 [18]). Intervessel pits alternate and are small with an average diameter (vertical) of 4–5 μm. Vessel ray pits are similar to intervessel pits. The tracheids and fibers are very thin walled. The axial parenchyma is paratracheal. Rays are exclusively uni- or multiseriate and homocellular (Plate 2 [18]).

The combination of rather large vessels, paratracheal axial parenchyma, and homocellular cells with relatively small, mainly uniseriate wood rays indicate that the wood belongs to Leguminosae.

4.7. *Monimiaceae*

Four pieces of fossil wood (specimens 2, 10, 14, and 15) can be attributed to the Monimiaceae. Among them, specimen 2 (Plate 2 [19, 20]) is almost black with cracks filled with white quartz. Through transmitted light, the material appears gray, and the rays are gray. At higher magnification, the organic material appears reddish orange. It is probably from a tree branch, in that the secondary wood shows a strong concentric structure. Specimens 14 (Plates 2 [21] and 3 [22]), 15 (Plate 3 [23]), and 10 resemble specimen 2 in look and preservation.

The wood of specimen 2, which closely resembles that of 14 and 15 in its anatomy, is diffuse porous (Plate 2 [19]). Vessels are distributed in no specific pattern, exclusively solitary (14 and 15), and in short (1–2 vessels) radial rows (2, Plate 2 [19, 20]). Perforation plates, intervessel pits, and vessel ray pits are all scalariform (15, Plate 3 [23]). Axial parenchyma is present (paratracheal in 14 and 15). Rays are uni- or multiseriate (in 14 multiseriate), up to 10 cells wide and extremely high at >2000 μm (Plate 2 [21]). Rays are composed of two or more cell types (heterocellular) (14, Plate 3 [22]). Sheath cells are present in specimen 14 (Plate 2 [21]). Growth ring boundaries are indistinct in specimens 2 and 15 and absent in specimen 14.

The characteristics of the wood with solitary vessels in combination with scalariform elements (perforation plates, intervessel pits, vessel ray pits) and partly extreme high and heterocellular rays points to a member of the Monimiaceae. The relatively good preservation of specimen 2 shows all relevant structures that could be found in a representative of the genus *Laurelia*. The only difference from a modern *Laurelia* is the dimension of the vertical vessel. The average diameter of a vessel in specimen 2 is smaller than found in modern *Laurelia*, but this could be due to its origin from a branch. In specimen 15, the wood structure is very similar; it probably also comes from a tree close to modern *Laurelia*.

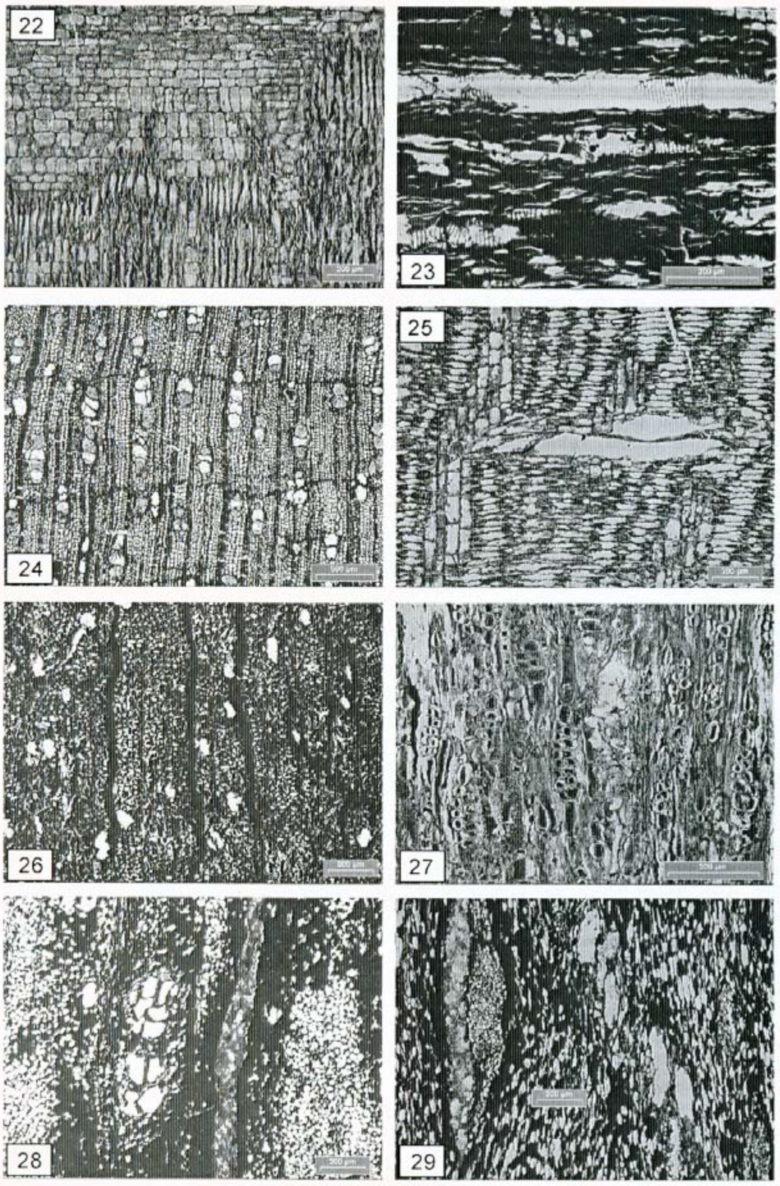

Plate 3. (22 and 23) Monimiaceae, (22) radial section of specimen 14, scale bar 200 μm; (23) radial section of specimen 15, scalariform perforation plates, intervessel and vessel ray pits, scale bar 200 μm. (24 and 25) Myristicaceae, (24) transverse section of specimen 4, scale bar 500 μm; (25) radial section of specimen 13, scale bar 200 μm. (26 and 27) Myrtaceae, (26) transverse section of specimen 3, scale bar 200 μm; (27) tangential section of specimen 7, scale bar 200 μm. (28 and 29) Proteaceae, (28) transverse section of specimen 8, vessels arranged in clusters, scale bar 200 μm; (29) tangential section of specimen 8, scale bar 200 μm.

In specimen 14, the rays are larger, but the wood anatomy still fits with that of a Monimiaceae, as in the modern genus *Hedycarya*. Specimen 10 is quantitative different from *Laurelia* and *Hedycarya*, but in its basal anatomy, it is a representative of Monimiaceae.

4.8. *Myristicaceae*

Two of the analyzed pieces of fossil woods (specimens 4 and 13) belong to the family Myristicaceae. Specimens 4 (Plate 3 [24]) and 13 (Plate 3 [25]) are black. Through transmitted light, the material is predominantly gray to black, and the rays in are gray specimen 4 are gray and dark gray to red in specimen 13. At higher magnification, the organic material in both specimens appears pale red to reddish brown.

The wood of specimen 4 is diffuse porous. Vessels are distributed in no specific pattern, in multiples, and commonly in short (2–3 vessels) radial rows (Plate 3 [24]). Perforation plates are scalariform. Intervessel pits alternate and have an average diameter (vertical) of 8–10 μm. Vessel ray pits are simple. Regarding tracheids and fibers, the fibers are very thin walled and occur in radial alignment (Plate 3 [24]). The axial parenchyma is banded marginally. The wood rays are multiseriate, 1–3 cells wide. Growth ring boundaries are distinct (Plate 3 [24]).

The anatomy of the wood in specimen 13 is similar to that of specimen 4. The shape of solitary vessels is irregular. Perforation plates are simple (Plate 3 [25]). Intervessel pits alternate. Vessel ray pits have reduced or distinct borders or appear simple. The rays are multiseriate, 1–3 cells wide (Plate 3 [25]). Growth ring boundaries are distinct and marked by marginal bands of parenchyma.

Scalariform perforations with alternating pits occur in the vessels of specimen 4. In addition, the fibers have relatively large lumina. These characteristics are found in the Myristicaceae, of which recent species occur mainly in the Pacific zone, Asia, central Africa, and tropical South America (Watson and Dallwitz, 1992). Usually the wood of the Myristicaceae is not very resistant and rapidly destroyed by insects and fungi (Sachsse, 1991). The anatomy of specimen 13 differs from that of specimen 4 only slightly and probably comes from a similar tree, perhaps even of the same genus. Due to moderate preservation, some important determination characters can no longer be observed.

4.9. *Myrtaceae*

Three wood fragments can be included in Myrtaceae (specimens 1, 3, and 7). The silicified wood of specimen 1 is black and transected by filled white cracks. Specimen 3 (Plate 3 [26]) is black. Through transmitted light, the material is brownish, and the rays are black. At higher magnification, the organic material appears brown.

Specimen 7 (Plate 3 [27]) is black. Through transmitted light, the material and the rays are orange brown. At higher magnification, the organic material appears dark orange to brown with white dots inside.

The wood anatomy of specimen 3 is very similar to specimen 7. The wood is diffuse porous, and vessels are distributed in no specific pattern but are exclusively solitary (Plate 3 [26]). Perforation plates are simple, and intervessel pits alternate. Vessel ray pits are similar to intervessel pits. In specimen 3, there are few vessels per square millimeter. Vascular or vasicentric tracheids are present. Axial parenchyma is present and in diffuse arrangement and diffuse organized in aggregates (7) or apotracheal and diffuse (13). Wood rays are composed of two or more cell types (heterocellular) (7, Plate 3 [27]). Heterocellular rays consist of square and upright cells in specimen 7 (Plate 3 [27]). Growth ring boundaries are distinct.

In specimen 3, the combination of solitary vessels and heterocellular wood rays in rows and the presence of diffuse axial parenchyma points to Myrtaceae. The enlarged cells indicate the former presence of crystals, which is diagnostic of wood of this family. Specimen 3 resembles the anatomy of wood found in the recent *Myrtus luma*. The structure of the wood in specimen 7 closely resembles that of 3 but is not well preserved; the rather small cells are deformed, and it is not evident whether pores are solitary. This wood belongs to a member of the Myrtaceae, but due to differences with specimen 3, it may belong to a different genus of this family.

4.10. *Proteaceae*

One specimen (8) belongs to the family Proteaceae. The silicified wood of specimen 8 (Plate 3 [28, 29]) is dark gray with cracks filled with white quartz. Through transmitted light, the material appears gray to black, and the rays are dark gray. At higher magnification, the organic material appears red to reddish brown.

The wood is diffuse porous. Vessels are arranged in tangential bands with no specific pattern and in multiples, commonly in clusters (Plate 3 [28]). Perforation plates are simple. Intervessel pits alternate. Vessel ray pits are rounded or angular. The axial parenchyma is paratracheal. Wood rays are multiseriate (1–15 cells wide), and larger rays are very wide (Plate 3 [29]). One or two occur per tangential millimeter.

The combination of vessels occurring in groups and clusters connected to extremely wide wood rays points to Proteaceae.

5. Diagenesis of the fossil woods

All samples suggest a relatively rapid silicification. The predominating substance found in the analyzed fossil woods is SiO_2, identified as microcrystalline chalcedony, quartz, and opal that fill the secondary cracks. SiO_2 maturity in woods provides information about their age (Landmesser, 1999) or postdiagenetic history. Because

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