The LINNEAN SOCIETY of London BOTANICAL Journal of the Linnean Society

Botanical Journal of the Linnean Society, 2016, **182**, 744–756. With 4 figures

Multilayered structure of tension wood cell walls in Salicaceae *sensu lato* and its taxonomic significance

BARBARA GHISLAIN[1]*, ERIC-ANDRÉ NICOLINI[2], RAÏSSA ROMAIN[1], JULIEN RUELLE[3], ARATA YOSHINAGA[4], MAC H. ALFORD[5] and BRUNO CLAIR[1]

[1]*CNRS, UMR EcoFoG, AgroParisTech, Cirad, INRA, Université des Antilles, Université de Guyane, Kourou 97310, France*
[2]*CIRAD, AMAP, botAnique et bioinforMatique de l'Architecture des Plantes, Campus Agronomique, BP 701, Kourou 97310, France*
[3]*INRA, Laboratoire d'Etude des Ressources Forêt-Bois (LERFoB), 54280 Champenoux, Nancy, France*
[4]*Laboratory of Tree Cell Biology, Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan*
[5]*Department of Biological Sciences, University of Southern Mississippi, 118 College Drive #5018, Hattiesburg, MS 39406, USA*

Received 29 February 2016; revised 3 June 2016; accepted for publication 11 July 2016

Salicaceae have been enlarged to include a majority of the species formerly placed in the polyphyletic tropical Flacourtiaceae. Several studies have reported a peculiar and infrequently formed multilayered structure of tension wood in four of the tropical genera. Tension wood is a tissue produced by trees to restore their vertical orientation and most studies have focused on trees developing tension wood by means of cellulose-rich, gelatinous fibres, as in *Populus* and *Salix* (Salicaceae *s.s.*). This study aims to determine if the multilayered structure of tension wood is an anatomical characteristic common in other Salicaceae and, if so, how its distribution correlates to phylogenetic relationships. Therefore, we studied the tension wood of 14 genera of Salicaceae and two genera of Achariaceae, one genus of Goupiaceae and one genus of Lacistemataceae, families closely related to Salicaceae or formerly placed in Flacourtiaceae. Opposite wood and tension wood were compared with light microscopy and three-dimensional laser scanning confocal microscopy. The results indicate that a multilayered structure of tension wood is common in the family except in *Salix*, *Populus* and one of their closest relatives, *Idesia polycarpa*. We suggest that tension wood may be a useful anatomical character in understanding phylogenetic relationships in Salicaceae. Further investigation is still needed on the tension wood of several other putatively close relatives of *Salix* and *Populus*, in particular *Bennettiodendron*, *Macrohasseltia* and *Itoa*. © 2016 The Linnean Society of London, *Botanical Journal of the Linnean Society*, 2016, **182**, 744–756

ADDITIONAL KEYWORDS: Flacourtiaceae – G-layer – multilayered tension wood – reaction wood.

INTRODUCTION

Until recently, morphological and anatomical characters were the primary sources of data for inferring phylogenetic relationships. More recently, DNA data have provided the majority of characters for our analyses of relationships, but reference to morphological characters remains useful for many reasons, including pedagogy, comparative evolutionary studies and studies of organisms for which DNA data are inaccessible (e.g. fossils, rare organisms). Wood anatomy has certainly proved useful (Tippo, 1946; Lens *et al.*, 2007; Christenhusz *et al.*, 2010), especially characters linked to cell organization, cell types or pitting. Here we show that fibre cell wall of reaction tissues, in this case tension wood, may also be useful phylogenetically.

Trees are able to optimize their orientation by the production of asymmetrical maturation stress around the tree. In angiosperms, a particular wood with high tensile stress, called tension wood, is produced on the upper side of the tilted stem. This high tensile

---

*Corresponding author. E-mail: barbara.ghislain@ecofog.gf stress allows for the active bending of the tree axis (Du & Yamamoto, 2007; Alméras & Fournier, 2009). Tension wood exhibits anatomical differences from normal wood, for example a lower frequency of vessels (Jourez, Riboux & Leclercq, 2001; Ruelle *et al.*, 2006). However, the greatest differences are observable at the fibre wall level. The secondary wall of a normal wood cell is composed of three sub-layers (S_1, S_2, S_3) made of cellulose microfibrils orientated at different angles and embedded in a matrix of lignin and hemicelluloses. Whereas S_1 and S_3 are thin, with cellulose microfibrils orientated to nearly 80° compared to the fibre axis, the S_2 layer is much thicker and the angle of microfibrils ranges from 10° to 20°. In tension wood the cell wall is generally modified by the presence of an inner unlignified layer, the so-called gelatinous layer or G-layer, replacing the S_3 and part of or the entire S_2 layer. It has been recently shown that this layer can be later lignified (Roussel & Clair, 2015). This partially explains why many species were known to produce tension wood lacking G-layers (Onaka, 1949; Fisher & Stevenson, 1981; Clair *et al.*, 2006). Whether lignified or not, the tension wood cell wall is homogeneous and characterized by a much lower (up to nil) cellulose microfibril angle compared to normal wood (Chaffey, 2000; Ruelle *et al.*, 2006).

A peculiar fibre wall structure was first discovered in xylem fibres of *Homalium foetidum* Benth., *Homalium luzoniense* Fern.-Vill. and *Olmediella betschleriana* Loes. (Bailey & Kerr, 1935; Daniel & Nilsson, 1996), in which the secondary wall appears multilayered. This cell wall structure was later demonstrated to occur only in tension wood (Clair *et al.*, 2006; Ruelle *et al.*, 2007a; Fig. 1). Daniel & Nilsson (1996) described this structure in *H. foetidum* as a succession of thick layers separated by thin layers with elevated levels of lignin. In *Laetia procera* Eichler, Ruelle *et al.* (2007a) described the thick layers as lightly lignified. Similar cell wall structures were also reported in reaction phloem fibres (Nanko, Saiki & Harada, 1982; Nakagawa, Yoshinaga & Takabe, 2012, 2014). In phloem fibres of *Populus* × *canadensis* Moench, Nanko *et al.* (1982) observed that the maximum number of layers was on the upper side of the tilted axis and decreased to that of normal phloem on the other side. They concluded that the number of layers is related to the intensity of tension wood. Nakagawa *et al.* (2012) observed multilayered fibres in opposite phloem in *Mallotus japonicus* (L.f.) Müll.Arg. (Euphorbiaceae), but they demonstrated an increase in the number of layers from opposite phloem to reaction phloem. In addition, *M. japonicus* and *Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg. (Euphorbiaceae) were reported to form a multilayered secondary wall structure in their tension wood fibres (Encinas & Daniel, 1997; Nakagawa *et al.*, 2012), whereas *Dipterocarpus* C.F.Gaertn. (Dipterocarpaceae), *Dillenia* L. (Dilleniaceae), *Laurelia* Juss. (Atherospermataceae) and *Elateriospermum* Blume (Euphorbiaceae) formed it in wood fibres, without specifying it was tension wood (Daniel & Nilsson, 1996).

The observation of this multilayered structure raises many questions about its role and the benefits for the plant compared to usual G-layers. Clair *et al.* (2006) showed that tensile stress measured on *Casearia javitensis* Kunth, a species with multilayered G-layer, is among the highest compared to the other 21 species measured, but they did not show a gap compared to other tension wood types. Ruelle *et al.* (2007b) obtained similar results for *L. procera*, compared to ten species.

This atypical structure is reported in five species of Salicaceae, all belonging to the former Flacourtiaceae: *H. luzoniense* and *O. betschleriana* (Bailey & Kerr, 1935), *H. foetidum* (Daniel & Nilsson, 1996), *C. javitensis* (Clair *et al.*, 2006) and *L. procera* (Ruelle *et al.*, 2007a). These results contrast with observations recorded from Salicaceae *s.s.* (*Salix* L. and *Populus* L.). Indeed, tension wood has been extensively studied in *Populus*, considered as a model plant for studies of angiosperms (Pilate *et al.*, 2004). These numerous studies report observations of tension wood cell walls with various techniques such as transmission electron microscopy (Araki *et al.*, 1982; Yoshinaga *et al.*, 2012), atomic force microscopy, scanning electron microscopy (Clair & Thibaut, 2001), confocal Raman microscopy (Gierlinger & Schwanninger, 2006), UV or bright field microscopy (Yoshinaga *et al.*, 2012) and phase contrast microscopy (Abedini *et al.*, 2015; Chang *et al.*, 2015). All these observations describe tension wood cell walls in *Populus* as a single-walled G-layer (Fig. 1). *Salix* is also known to have single-walled G-layers (Gritsch *et al.*, 2015). In this paper, we will name these single-layered G-layers as ‘usual G-layer’ in contrast to ‘multilayered G-layer’ or ‘multilayered fibres’ for G-layers composed of two or more layers (Fig. 1). Both may be lignified or not.

Salicaceae *s.s.*, composed of *Populus* and *Salix*, have been recently enriched with numerous genera from the former Flacourtiaceae (Chase *et al.*, 2002), the latter family being hard to characterize because it served as a depository, or ‘garbage bag’, for taxa with uncertain affinities (Chase *et al.*, 2002). Several studies have provided molecular and/or morphological data that support the realignment of most of the genera and species to Salicaceae or Achariaceae (Chase *et al.*, 2002; Alford, 2005; Xi, *et al.*, 2012), but there is still discussion about whether the non-

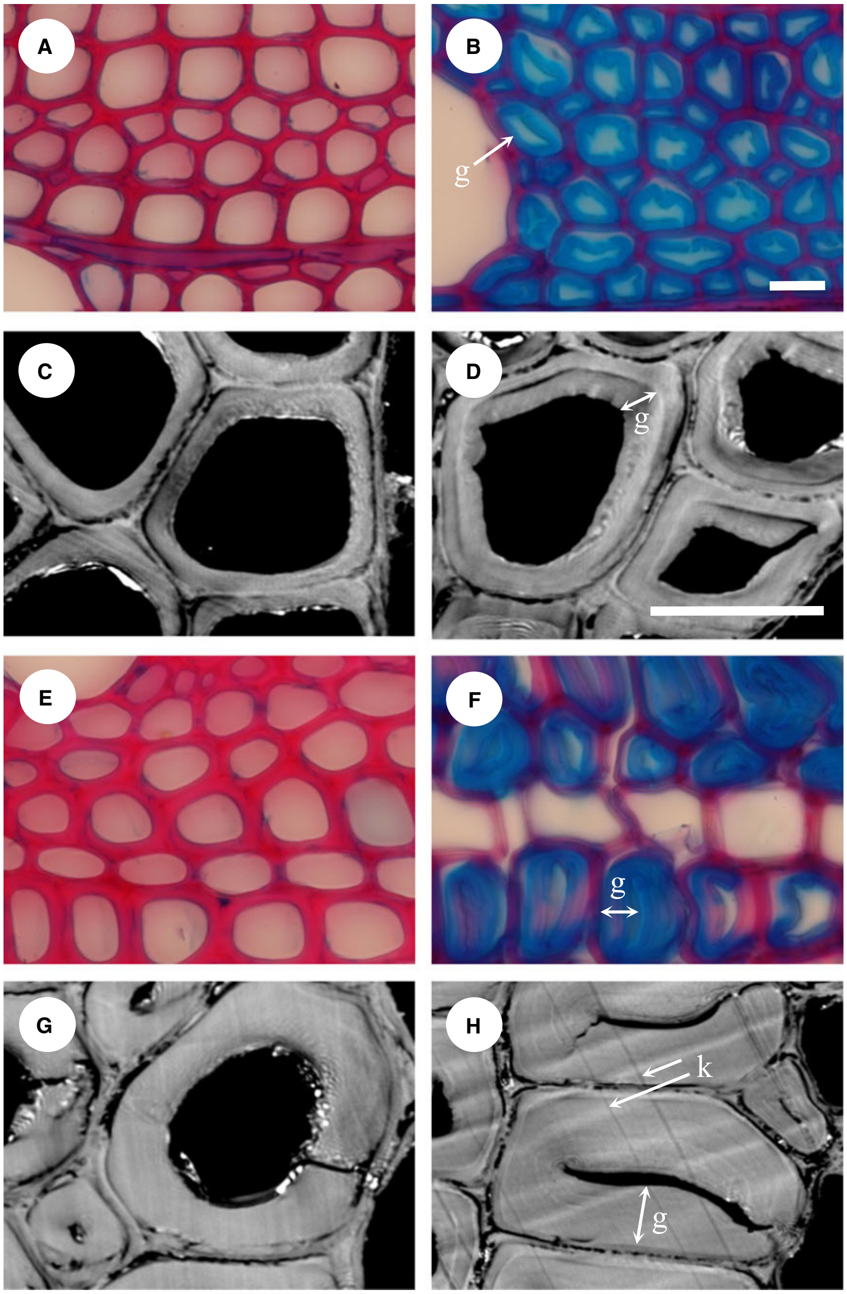


Figure 1. Comparison of normal wood (A, C, E, G) and tension wood (B, D, F, H) fibre wall in *Populus* (A–D) and *Laetia procera* (E–H) observed in bright field after staining with Safranin/Alcian blue, scale bar = 20 μm (A, B, E, F) and with a 3D laser scanning confocal microscope, scale bar = 10 μm (C, D, G, H). *Populus* tension wood is characterized by a typical unlignified G-layer and *Laetia* tension wood by a multilayered G-layer. Arrows indicate the G-layer and/or its thickness (g) and an artefact of residual traces of the diamond knife (k).

cyanogenic Flacourtiaceae should be treated in a Salicaceae *s.l.* or subdivided even further into Samydaceae, Scyphostegiaceae and Salicaceae *sensu medio* (Alford, 2005; Samarakoon, 2015). Alford (2005) argued for the latter because he could find no morphological characters that supported Salicaceae *s.l.*, whereas several synapomorphies supported recognition of Samydaceae, Scyphostegiaceae and Salicaceae *sensu medio*. Given these questions of circumscription and the variation in tension wood cell walls, tension wood characters may prove to be a unifying feature or synapomorphy of Salicaceae *s.l.* that was later lost in *Salix*, *Populus* and their closest relatives.

This study aims to answer how this particular multilayered tension wood is distributed among the species newly classified in Salicaceae. The topic of this study is two-fold: (1) to clarify the expression of this peculiar tension wood and (2) to generate new anatomical data for Salicaceae. Here, we investigate: (1) the characteristics of multilayered tension wood and (2) whether the multilayered cell wall is a characteristic of all former Flacourtiaceae now integrated in Salicaceae. Achariaceae, Goupiaceae and Lacistemataceae, three families formerly included in or closely linked to Flacourtiaceae, were also examined for a broader understanding of the distribution of this anatomical character.

MATERIAL AND METHODS

Naturally tilted branches or main axes of Salicaceae were collected in natural forest in four places in French Guiana and Guadeloupe or were provided by the Lyon Botanical Garden (France), the Nancy Botanical Garden (France), the Strasbourg University Botanical Garden (France) and the experimental unit of Villa-Thuret (INRA, France) (Table 1). Thirty-one species belonging to 14 genera from Salicaceae were studied. The selected genera were drawn from five of the nine tribes of the family, encompassing the major morphological groups. Some of the species are represented by several individuals. Additionally, two species of Achariaceae, one species of Goupiaceae and three species of Lacistemataceae were added to this study because of their former inclusion in or close relationship to Flacourtiaceae. Finally, because of the surprising results obtained from *Idesia* Maxim. collected in a botanical garden, a 3-year-old tree of *Idesia polycarpa* Maxim. collected at the Kitashirakawa Experimental Station of the Field Science Education and Research Center of Kyoto University in Japan was artificially tilted to ensure the production of tension wood. The list of species and their provenances are given in Table 1. Table 2 lists the genera belonging to Salicaceae and highlights the genera observed in the study.

Tension wood was confirmed by the presence of eccentric growth with more wood produced on the upper side of the axis. Sample preparation and observations were performed in Kourou, French Guiana.

Three-dimensional (3D) laser scanning confocal microscopy

Tension wood samples were observed with a 3D laser scanning confocal microscope (Keyence VK-9710K). This technique allows for the observation of the topography of the surface of a sample with a resolution of 10 nm. Observations were made on untreated dry wood blocks after smoothing the surface with a diamond knife on a rotary microtome. This sample preparation produces a nearly perfect surface. However, changes in organization or composition from layer to layer create some topographic traces at the surface of the sample, allowing easy identification of the cell wall layers or sub-layers.

Optical microscopy

Wood samples were kept wet until sectioning. Sections 20–50 μm thick were produced with a sliding microtome and stained with Safranin and Alcian blue 8GX in order to observe lignin distribution. Mounted on glass slides, they were observed under bright field with an optical microscope (Olympus BX2). Unstained sections 2–3 μm thick were produced from some species for UV microscopy to validate results obtained via Safranin/Alcian blue staining. These sections were observed under the same microscope but equipped with a mercury lamp (USH102D USHIO) that generates light filtered with fluorescence filter cubes U-MNU2 (Olympus, excitation filter: 360–370 nm, dichromatic mirror: 400 nm, emission filter: 420 nm). Lignified cell wall autofluoresces, whereas unlignified layers such as the G-layer remain dark (Roussel & Clair, 2015).

RESULTS

Figure 2 presents tension wood fibres of some of the studied species observed with laser scanning confocal microscopy (see Supporting Information, Fig. S1 for other species). Figure 3 presents the anatomical sections of seven species stained with Safranin/Alcian blue and observed in bright field with optical microscopy.

A multilayered structure in tension wood cell walls is observable in all former Flacourtiaceae, except in *I. polycarpa*, and is absent in all studied species from Salicaceae *s.s.* (*Populus* and *Salix*), Achariaceae, Goupiaceae and Lacistemataceae (Fig. 2). A thick S_2 layer is sometimes present and should not to be confused with the G-layer, which often stands out because it detaches from other layers during sectioning (Clair, Thibaut & Sugiyama, 2005).

The maximum number of layers in a multilayered wall varies from species to species. Most of the species show only two layers, but there can be up to six layers in *Casearia sylvestris* Sw. or *Neoptychocarpus apodanthus* (Kuhlm.) Buchheim (Table 2).

Table 1. Species of trees used in this study

Genera	Species	Family	*N*	V	Sampling location
Carpotroche	sp.	Achariaceae	3	RR2, RR3, RR4	Paracou, Sinamary, FG
Kiggelaria	*africana*		2		Lyon botanical garden, Villa-Thuret Experimental garden (INRA), Antibes
Goupia	sp.	Goupiaceae	1		Montagne des singes, Kourou, FG
Lacistema	*aggregatum*	Lacistemataceae	1	RR21	Paracou, Sinamary, FG
Lacistema	*pubescens*	Lacistemataceae	1	RR22	Paracou, Sinamary, FG
Lacistema	sp.	Lacistemataceae	1	RR23	Montagne des singes, Kourou, FG
Azara	*dentata*	Former Flacourtiaceae	1		Lyon Botanical Garden
Banara	*guianensis*	Former Flacourtiaceae	1	RR1	Montagne des singes, Kourou, FG
Carrierea	*calycina*	Former Flacourtiaceae	1		Strasbourg University Botanical Garden
Casearia	cf *decandra*	Former Flacourtiaceae	3	RR5, RR6, RR7	Paracou, Sinamary, FG
Casearia	*commersoniana*	Former Flacourtiaceae	1	RR8	Paracou, Sinamary, FG
Casearia	*grandiflora*	Former Flacourtiaceae	1	RR9	Piste Paul Isnard, Saint-Laurent, FG
Casearia	*guianensis*	Former Flacourtiaceae	2	RR10, RR11	Crique Passoura, Kourou, FG
Casearia	*javitensis*	Former Flacourtiaceae	2	RR12, RR13	Crique Passoura, Kourou, FG, Montagne des singes, Kourou, FG
Casearia	*pitumba*	Former Flacourtiaceae	3	RR14, RR15, RR16	Montagne des singes, Kourou, FG
Casearia	*sylvestris*	Former Flacourtiaceae	3	RR17, RR18, RR19	Paracou, Sinamary, FG
Dovyalis	*caffra*	Former Flacourtiaceae	2		Strasbourg University Botanical Garden, Villa-Thuret Experimental garden (INRA), Antibes
Homalium	*guianense*	Former Flacourtiaceae	1	RR20	Crique Passoura, Kourou, FG
Homalium	*racemosum*	Former Flacourtiaceae	1		Guadeloupe
Idesia	*polycarpa*	Former Flacourtiaceae	2		Kyoto University FSERC(JP), Strasbourg University Botanical Garden
Laetia	*procera*	Former Flacourtiaceae	1	RR24	Montagne des singes, Kourou, FG
Neoptychocarpus	*apodanthus*	Former Flacourtiaceae	1	RR25	Paracou, Sinamary, FG
Poliothyrsis	*sinensis*	Former Flacourtiaceae	2		Strasbourg University Botanical Garden, Villa-Thuret Experimental garden (INRA), Antibes
Ryania	speciosa speciosa var. bicolor	Former Flacourtiaceae	2	RR26, RR27	Paracou, Sinamary, FG, Montagne des singes, Kourou, FG
Xylosma	*benthamii*	Former Flacourtiaceae	1	RR28	Paracou, Sinamary, FG
Xylosma	*congesta*	Former Flacourtiaceae	1		Villa-Thuret Experimental garden (INRA), Antibes
Xylosma	*flexuosa*	Former Flacourtiaceae	1		Strasbourg University Botanical Garden
Xylosma	*japonica*	Former Flacourtiaceae	1		Strasbourg University Botanical Garden
Populus	*alba*	Salicaceae s.s.	1		Nancy Botanical Garden
Populus	*nigra (italica)*	Salicaceae s.s.	1		Nancy Botanical Garden
Populus	*trichocarpa*	Salicaceae s.s.	1		Nancy Botanical Garden
Populus	*deltoides* × *nigra*	Salicaceae s.s.	1		Nancy Botanical Garden
Salix	*lucida*	Salicaceae s.s.	1		Nancy Botanical Garden
Salix	*myrsinifolia*	Salicaceae s.s.	1		Nancy Botanical Garden
Salix	*purpurea*	Salicaceae s.s.	1		Nancy Botanical Garden

Samples were collected in Europe (France), the Caribbean (Guadeloupe), South America (French Guiana) and Asia (Japan). Location of sampling performed in French Guiana is presented as: Place name, nearest city, FG. *N*, number of trees collected; V, reference of the vouchers deposited in the herbarium “Herbier IRD de Guyane” (CAY); FG, French Guiana; JP, Japan; FSERC, Field Science Education and Research Center.

Table 2. Genera of Salicaceae studied, based on Chase *et al.* (2002)

Subfamily	Tribe	Genera	Described species	No. of layers	Tension wood lignification
Incertae sedis		*Oncoba*			
Salicoideae	Abatieae	*Abatia*			
		Aphaerema			
	Bembicieae	*Bembicia*			
	Flacourtieae	*Azara*	1	1–3	Unlignified
		Bennettiodendron			
		Carrierea	1	1–2	Unlignified
		Dovyalis	1	1–3	Partly lignified or unlignified
		Flacourtia			
		Idesia	1	1	Unlignified
		Itoa			
		Lasiochlamys			
		Ludia			
		Olmediella			
		Poliothyrsis	1	1–3	Unlignified
		Priamosia			
		Tisonia			
		Xylosma	4	1–3 (*flexuosa*) 2–3 (*japonica*) 1–4 (*benthamii*, *congesta*)	Partly lignified
	Homalieae	*Bartholomaea*			
		Bivinia			
		Byrsanthus			
		Calantica			
		Dissomeria			
		*Gerrardina**			
		Homalium	2	1–3 (*guianense*) 1–4 (*racemosum*)	Partly lignified
		Neopringlea			
		Trimeria			
	Prockieae	*Banara*	1	2–3	Lignified
		Hasseltia			
		Hasseltiopsis			
		Macrohasseltia			
		Neosprucea			
		Pineda			
		Pleuranthodendron			
		Prockia			
	Saliceae	*Populus*	4	1	Unlignified
		Salix	3	1	Partly lignified or unlignified
	Scolopieae	*Hemiscolopia*			
		Mocquerysia			
		Phyllobotryon			
		Phylloclinium			
		Pseudoscolopia			
		Scolopia			

Table 2. *Continued*

Subfamily	Tribe	Genera	Described species	No. of layers	Tension wood lignification
Samydoideae	Samydeae	*Casearia*	8	1–3 (*grandiflora*, *guianensis*, *javitensis*, *pitumba*) 1–4 (cf. *decandra*, *javitensis*, *sylvestris*) 2–4 (cf. *decandra*, *pitumba*) 1–5 (*commersoniana*, *sylvestris*) 1–6 (*sylvestris*)	Lignified or partly lignified
		Euceraea			
		Hecatostemon			
		Laetia	1	1–5	Partly lignified
		Lunania			
		Neoptychocarpus	1	1–6	Lignified
		Ophiobotrys			
		Osmelia			
		Pseudosmelia			
		Ryania	2	1–3	Partly lignified
		Samyda			
		Tetrathylacium			
		Zuelania			
Scyphostegioideae		*Scyphostegia*			

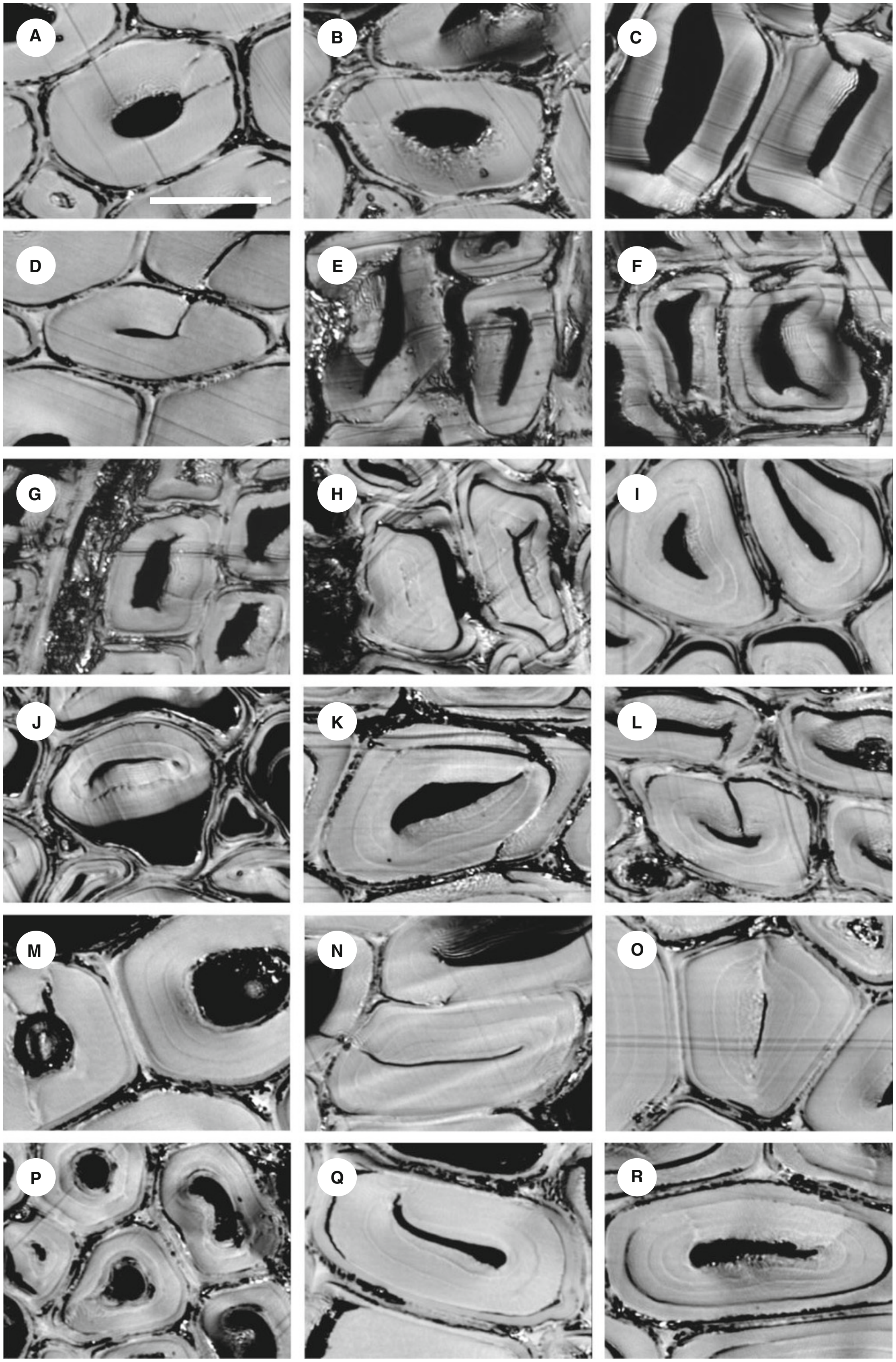
The column ‘Described species’ indicates the number of species observed in a given genus. Tension wood cell wall, the number of layers of the G-layer (min. − max.) and the presence of lignification of the G-layer are described.

*This genus has now been moved to a distantly related family (Alford, 2006).

For a given species, the number of layers also varies. In particular, monolayered G-layers, i.e. usual G-layers, can be found near multilayered G-layers for some species. In a single tension wood specimen, the number of layers increases progressively from cell to cell from one to multiple layers. Consequently, usual G-layers are hardly found near multilayered fibres. In a limited number of samples, the multilayered fibres are scarce and hard to find amid the usual G-layers [e.g. *Dovyalis caffra* (Hook.f. & Harv.) Warb. from Villa-Thuret Experimental Garden, INRA]. Whenever multilayered tension wood fibres occur they are often found in intense zones of tension wood, i.e. centred in the arc of tension wood.

For all species, the thin interlayers of multilayered tension wood cell wall appear lignified as described by Ruelle *et al.* (2007a). In some of the species, thick layers of multilayered tension wood cell wall appeared lignified with Safranin/Alcian blue staining (confirmed on unstained samples under UV light) (Fig. 3, Table 2). For instance, all multilayers of *Banara guianensis* Aubl. appear lignified, whereas only some multilayers were lignified in *C. sylvestris*. Multilayers appear unlignified in a few species,

Figure 2. Transverse sections of tension wood fibres observed with a 3D laser scanning confocal microscope. Scale bar = 10 μm. A, B, Achariaceae; C, Goupiaceae; D, Lacistemataceae; E–R, Salicaceae *s.l.* A, *Carpotroche* sp.; B, *Kiggelaria africana*; C, *Goupia* sp.; D, *Lacistema aggregatum*; E, *Idesia polycarpa* (sampled in an artificially tilted tree); F, *Populus alba* (thick S_2 layer); G, *Salix lucida*; H, *Azara dentata*; I, *Banara guianensis*; J, *Carrierea calycina*; K, *Casearia* cf. *decandra*; L, *Dovyalis caffra*; M, *Homalium guianense*; N, *Laetia procera*; O, *Neoptychocarpus apodanthus*; P, *Poliothyrsis sinensis*; Q, *Ryania speciosa*; R, *Xylosma benthamii*. A–G, one layer observed in the G-layer; H–R, more than two layers observed in the G-layer.


A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R

including *Azara dentata* Ruiz & Pav. and *Carrierea calycina* Franch. (Table 2). Thick layers of the tension wood cell wall of *D. caffra* are unlignified on the sample from Villa-Thuret Experimental Garden (INRA), but partly lignified on the sample from the Strasbourg University Botanical Garden. Similarly, the thick layer of tension wood cell wall of *L. procera* looks partially lignified in our sampling, whereas Ruelle *et al.* (2007a) found these layers unlignified with Safranin/Alcian blue staining, although slightly lignified with the Wiesner reaction.

DISCUSSION

Tension wood

Despite the scarcity of previous observations in the literature (Ruelle *et al.*, 2007a), we confirm that the multilayered wall occurs in the tension wood fibres of 11 genera and 21 species. When multilayered cell walls are formed, they are always observed on the upper side of the tilted axis, i.e. only in tension wood. We did not observe multilayered cell walls in axes without tension wood even when the given species is able to form multilayered wall cells. Thus, the position of sampling in the plant body for observing the presence or absence of such multilayered cells is critical. In this study, we collected only axes highly susceptible to have formed tension wood during past radial growth (tilted branches or bent main axis). So the present investigations give a clear idea of the distribution of the multilayered cells in tension wood of these species of Salicaceae.

Variability in the number of layers and in the distribution of multilayered wall in tension wood

The number of layers of the tension wood cell wall varies between species, but also within a species or within a single individual. Within a sample, tension wood with the usual G-layer can occur near multilayered fibres. Similar observations was made by Daniel & Nilsson (1996), although the authors did not identify this peculiar structure to be a characteristic of tension wood. At the species level, the tilted branch of *L. procera* showed here a variation from one to five layers, whereas four to eight layers were observed by Ruelle *et al.* (2007*b*) on naturally tilted trees. We suspect that the number of layers of one species would be linked to the intensity of reaction wood formation, as has been shown for reaction phloem fibres (Nanko *et al.*, 1982). It also seems that some species may have a higher maximal number of layers. Nevertheless, such conclusions cannot be reached at this point and would require a more complete study with artificially tilted stems grown in a controlled environment. It would also be interesting to investigate if the formation of the usual G-layer or multilayered G-layer depends on the mechanical stimulus. For example, in *D. caffra* from Villa-Thuret Experimental Garden (INRA), most fibres formed a typical G-layer and few multilayered fibres occurred. One can wonder whether the degree of mechanical stimulus has an effect on the resulting fibre wall structure in some species and would this have a bearing on the distinction between the former Flacourtiaceae and Salicaceae *s.s*.

Tension wood and lignification

In *H. foetidum* (Daniel & Nilsson, 1996), the thick layers show weak lignification whereas in *L. procera* (Ruelle *et al.*, 2007a), some multilayered fibres are even more lignified than other multilayered fibres. The role of lignification in tension wood is not fully understood yet and is still being investigated (Roussel & Clair, 2015). It is, for instance, not clear whether lignification would occur in some species and not in others or whether it is a result of a peculiar environment or mechanical stimulus. Does *D. caffra* lignify or not in reaction to the environment or, for example, due to plant ontogeny (Roussel & Clair, 2015) or some other unknown factor? It can nonetheless be noted that we did not observe an obvious pattern of lignification at the level of a species or a genus. A better understanding of the triggers and the role of lignification in tension wood will be necessary to further interpret our observations.

Tension wood fibre wall structure and phylogeny

Although our sample does not include all genera and species of Salicaceae, our results give a clearer representation of the family on the basis of this anatomical character. Chase *et al.* (2002) proposed nine tribes constituting the family (Table 3), primarily following Lemke (1988). We studied 14 genera in five tribes. The seven species studied in tribe Saliceae (*Populus* and *Salix*) did not show multilayered walls. Conversely, among the 12 genera and 24 species studied from the four other tribes, all species except *I. polycarpa* exhibited multilayered tension wood fibre walls. Thereby, among the genera observed in this study (representing 27% of the genera in this last group of tribes), nearly all showed multilayered tension wood cell walls, supporting the idea that this anatomical character would also be present in most of the other non-studied genera.

Nevertheless, the particular exception is *I. polycarpa*, a species for which we could not find multilayered tension wood even within a zone of severe tension wood produced in an artificially tilted tree.

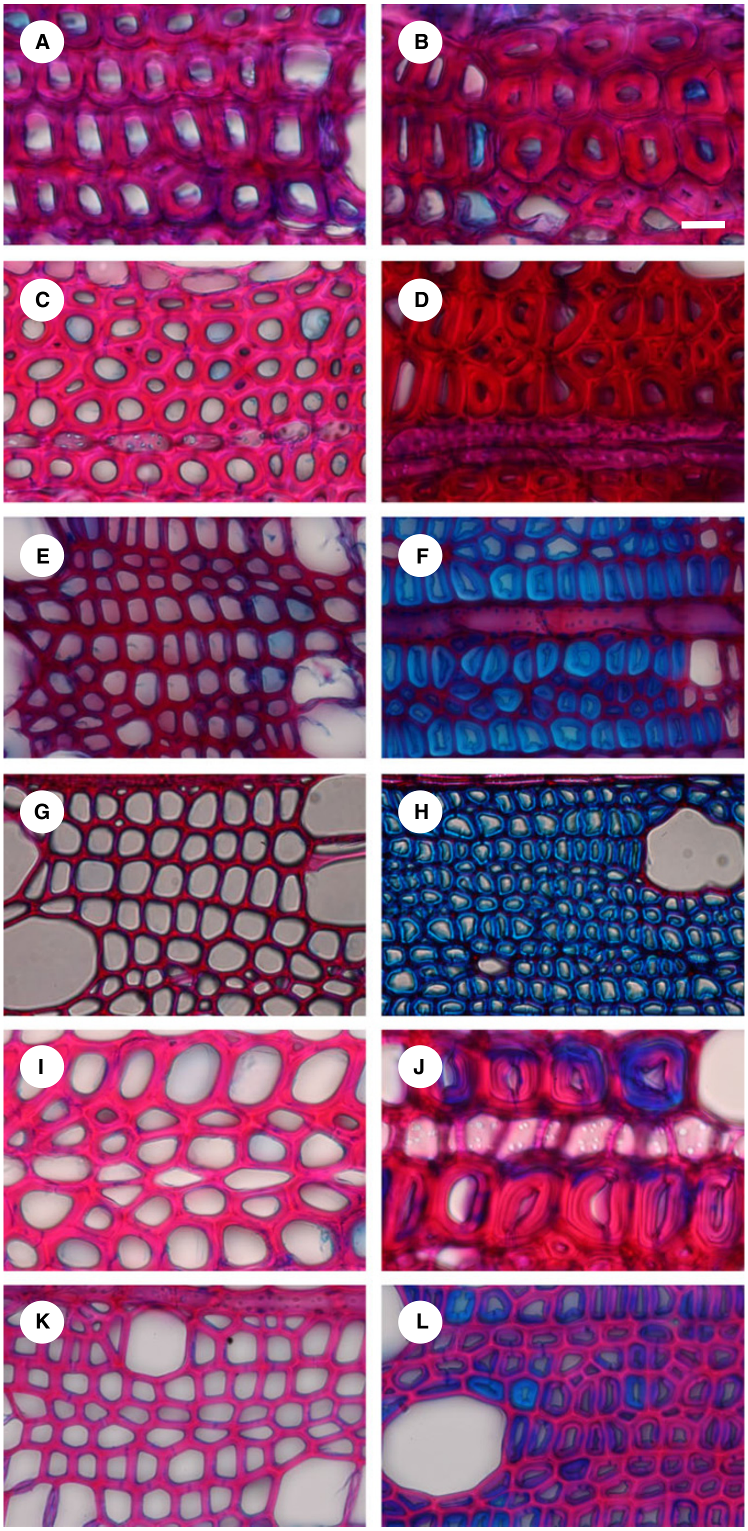


Figure 3. Transverse sections of opposite wood (A, C, E, G, I, K) and tension wood (B, D, F, H, J, L) stained with Safranin/Alcian blue. Scale bar = 20 μm. A, B, Achariaceae; C–L, Salicaceae *s.l.* A, B, *Carpotroche* sp.; C, D, *Banara guianensis*; E, F, *Carrierea calycina*; G, H, *Idesia polycarpa* (sampled in a naturally tilted tree); I, J, *Laetia procera*; K, L, *Salix lucida*. H, L, one layer observed in the G-layer; B, D, F, J, more than two layers observed in the G-layer. Note the presence of lignin in the G-layer.

Table 3. Number and percentage of the studied genera of Salicaceae and of the presence of multilayered walls in tension wood fibres in the studied genera

		Studied genera		Studied genera with multi-layered walls	
Tribe (or genus)	Genera Number	Number	%	Number	%
(*Oncoba*)	1	0	0	–	–
Flacourtieae	14	6	42	5 (- *Idesia*)	83
Homalieae	9	1	11	1	100
Saliceae	2	2	100	0	0
Scolopieae	6	0	0	–	–
Abatieae	2	0	0	–	–
Bembicieae	1	0	0	–	–
Prockieae	8	1	12	1	100
Samydeae	13	4	30	4	100
(*Scyphostegia*)	1	0	0	–	–
	57	14	24	11	78

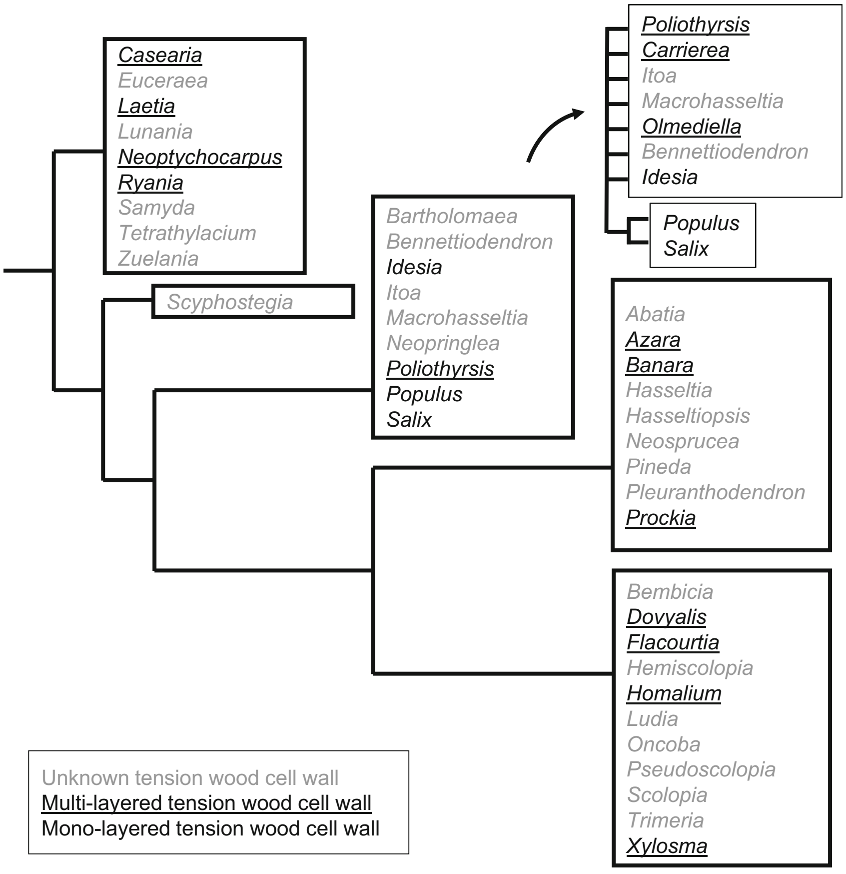


Figure 4. Schematic representation of phylogenetic relationships in Salicaceae *s.l.*, based on Chase *et al.* (2002) and Alford (2005). Arrow shows immediate relatives of *Salix* and *Populus* according to Alford (2005). Studied species and species from the literature are given in black. Species with multilayered tension wood are underlined.

Idesia polycarpa is therefore probably unable to form multilayered tension wood cell walls like both *Salix* and *Populus*. Indeed, long ago Hallier (1908, 1912) suggested that *I. polycarpa* is closely connected to Salicaceae, an idea relayed by Miller (1975) and supported by the phylogenetic analysis of morphological and DNA data (Leskinen & Alström-Rapaport, 1999; Alford, 2005). Miller (1975) suggested a close relationship between Salicaceae and some former Flacourtiaceae and attested to the close relationships in wood anatomy between *Idesia*, *Itoa* Hemsl., *Salix* and *Populus*.

Chase *et al.* (2002) clearly showed the close relationships between *Idesia*, *Benettiodendron* Merr., *Itoa*, *Poliothyrsis* Oliv. and *Salix* and *Populus*. Alford (2005) added *Carrierea* Franch., *Macrohasseltia* L.O.Williams and *Olmediella* Baill. to this clade (Fig. 4). In this clade, only *Poliothyrsis sinensis* Hook.f., *C. calycina* and *O. betschleriana* (Bailey & Kerr, 1935) produced multilayered tension wood cell walls. It would therefore be of interest to investigate the tension wood of species of *Bennettiodendron* Merr., *Macrohasseltia macroterantha* (Standl. & L.O.Williams) L.O.Williams and *Itoa orientalis* Hemsl. as no information about their tension wood is currently available. Due to the particular position of *I. polycarpa* and the limited phylogenetic resolution in this clade, the hypothesis is proposed that *I. polycarpa* and *Salix* and *Populus* may have a recent common ancestor that lost the ability to form multilayered tension wood.

Therefore, on the basis of the multilayered tension wood cell wall, Salicaceae appear structured in two parts: Salicaceae *s.s.* without multilayered tension wood fibre walls and the former Flacourtiaceae, with *I. polycarpa* (and perhaps *Bennettiodendron*, *M. macroterantha* and *I. orientalis*) positioned in between. The results clearly distinguish a core ex-Flacourtiaceae on the basis of tension wood. With morphological and genetic characters, tension wood is therefore a useful additional character for understanding the evolution of Salicaceae.

Although this anatomical feature was almost systematically present in the former Flacourtiaceae now classed in Salicaceae *s.l.*, it appears that several species of Euphorbiaceae, a family in the same order of angiosperms (Xi *et al.*, 2012), also developed it (Daniel & Nilsson, 1996; Encinas & Daniel, 1997; Nakagawa *et al.*, 2012; B. Ghislain and B. Clair, unpublished results) . Additional sampling there, too, may provide broader insights into the evolutionary significance of this character.

ACKNOWLEDGEMENTS

This work was supported by the French National Research Agency in the framework of the project 'StressInTrees' (ANR-12-BS09-0004). B.G. benefits from an 'Investissements d'Avenir' grant managed by French National Research Agency (CEBA, ANR-10-LABX-25-01). We thank Richard Bellanger from the experimental unit of Villa-Thuret (INRA), Frédérique Dumont from the Monaco Exotic Garden, Frédéric Pautz, Maxime Rome and David Scherberich from the Lyon Botanical Garden, Alain Rousteau (EcoFoG, Université des Antilles) for the collections in Guadeloupe, Jean-François Gonot and Laurent Péru from the Nancy Botanical Garden and Frédéric Tournay from the Strasbourg University Botanical Garden.

REFERENCES

Abedini R, Clair B, Pourtahmasi K, Laurans F, Arnould O. 2015. Cell wall thickening in developing tension wood of artificially bent poplar trees. *IAWA Journal* **36:** 44–57.

Alford MH. 2005. *Systematic studies in Flacourtiaceae*. Dissertation, Cornell University, Ithaca, NY.

Alford MH. 2006. Gerrardinaceae: a new family of African flowering plants unresolved among Brassicales, Huerteales, Malvales, and Sapindales. *Taxon* **55:** 959–964.

Alméras T, Fournier M. 2009. Biomechanical design and long-term stability of trees: morphological and wood traits involved in the balance between weight increase and the gravitropic reaction. *Journal of Theoretical Biology* **256:** 370–381.

Araki N, Fujita M, Saiki H, Harada H. 1982. Transition of the fiber wall structure from normal wood to tension wood in *Robinia pseudoacacia* L. and *Populus euramericana* Guinier. *Mokuzai Gakkaishi* **28:** 267–273.

Bailey IW, Kerr T. 1935. The visible structure of the secondary wall and its significance in physical and chemical investigations of tracheary cells and fibers. *Journal of the Arnold Arboretum* **16:** 273–300.

Chaffey N. 2000. Microfibril orientation in wood cells: new angles on an old topic. *Trends in Plant Science* **5:** 360–362.

Chang SS, Quignard F, Alméras T, Clair B. 2015. Mesoporosity changes from cambium to mature tension wood: a new step toward the understanding of maturation stress generation in trees. *New Phytologist* **205:** 1277–1287.

Chase MW, Zmarzty S, Lledó MD, Wurdack KJ, Swensen SM, Fay MF. 2002. When in doubt, put it in Flacourtiaceae: a molecular phylogenetic analysis based on plastid rbcL DNA sequences. *Kew Bulletin* **57:** 141–181.

Christenhusz MJM, Fay MF, Clarkson JJ, Gasson P, Morales Can J, Jiménez Barrios JB, Chase MW. 2010. Petenaeaceae, a new angiosperm family in Huerteales with a distant relationship to *Gerrardina* (Gerrardinaceae). *Botanical Journal of the Linnean Society* **164:** 16–25.

Clair B, Ruelle J, Beauchêne J, Prévost MF, Fournier M. 2006. Tension wood and opposite wood in 21 tropical rain forest species. 1. Occurrence and efficiency of G-layer. *IAWA Journal* **27:** 329–338.

Clair B, Thibaut B. 2001. Shrinkage of the gelatinous layer of poplar and beech tension wood. *IAWA Journal* **22:** 121–131.

Clair B, Thibaut B, Sugiyama J. 2005. On the detachment of the gelatinous layer in tension wood fiber. *Journal of Wood Science* **51:** 218–221.

Daniel G, Nilsson T. 1996. Polylaminate concentric cell wall layering in fibres of *Homalium foetidum* and its effect on degradation by microfungi. In: Donaldson LA, ed. *Third Pacific Regional Conference on Recent Advances in Wood Anatomy*. Rotorua: New Zealand Forest Research Institute, 369–372.

Du S, Yamamoto F. 2007. An overview of the biology of reaction wood formation. *Journal of Integrative Plant Biology* **49:** 131–143.

Encinas O, Daniel G. 1997. Degradation of the gelatinous layer in aspen and rubberwood by the blue stain fungus *Lasiodiplodia theobromae*. *IAWA Journal* **18:** 107–115.

Fisher JB, Stevenson JW. 1981. Occurrence of reaction wood in branches of dicotyledons and its role in tree architecture. *Botanical Gazette* **142:** 82–95.

Gierlinger N, Schwanninger M. 2006. Chemical imaging of poplar wood cell walls by confocal Raman microscopy. *Plant Physiology* **140:** 1246–1254.

Gritsch C, Wan Y, Mitchell RAC, Shewry PR, Hanley SJ, Karp A. 2015. G-fibre cell wall development in willow stems during tension wood induction. *Journal of Experimental Botany* **66:** 6447–6459.

Hallier H. 1908. Uber Juliana, eine Terebinthaceen-Gattung mit Cupula, und die wahren Stammeltern de Kaitzchenblitler. *Beihefte zum Botanischen Centralblatt* **23:** 81–265.

Hallier H. 1912. L'origine et le système phylétique des angiospermes exposés à l'aide de leur arbre généalogique. *Archives Néerlandaises des Sciences Exactes et Naturelles Série* **3:** 146–234.

Jourez B, Riboux A, Leclercq A. 2001. Anatomical characteristics of tension wood and opposite wood in young inclined stems of poplar (*Populus euramericana* cv 'Ghoy'). *IAWA Journal* **22:** 133–157.

Lemke DE. 1988. A synopsis of Flacourtiaceae. *Aliso* **12:** 28–43.

Lens F, Schönenberger J, Baas P, Jansen S, Smets E. 2007. The role of wood anatomy in phylogeny reconstruction of Ericales. *Cladistics* **23:** 229–294.

Leskinen E, Alström-Rapaport C. 1999. Molecular phylogeny of Salicaceae and closely related Flacourtiaceae: evidence from 5.8 S, ITS 1 and ITS 2 of the rDNA. *Plant Systematics and Evolution* **215:** 209–227.

Miller RB. 1975. Systematic anatomy of the xylem and comments on the relationships of Flacourtiaceae. *Journal of the Arnold Arboretum* **56:** 20–102.

Nakagawa K, Yoshinaga A, Takabe K. 2012. Anatomy and lignin distribution in reaction phloem fibres of several Japanese hardwoods. *Annals of Botany* **110:** 897–904.

Nakagawa K, Yoshinaga A, Takabe K. 2014. Xylan deposition and lignification in the multi-layered cell walls of phloem fibres in *Mallotus japonicus* (Euphorbiaceae). *Tree Physiology* **34:** 1018–1029.

Nanko H, Saiki H, Harada H. 1982. Structural modification of secondary phloem fibers in the reaction phloem of *Populus euramericana*. *Mokuzai Gakkaishi* **28:** 202–207.

Onaka F. 1949. Studies on compression and tension wood. *Wood Research* **1:** 1–88.

Pilate G, Déjardin A, Laurans F, Leplé JC. 2004. Tension wood as a model for functional genomics of wood formation. *New Phytologist* **164:** 63–72.

Roussel J-R, Clair B. 2015. Evidence of the late lignification of the G-layer in *Simarouba* tension wood, to assist understanding how non-G-layer species produce tensile stress. *Tree Physiology* **35:** 1366–1377.

Ruelle J, Beauchene J, Thibaut A, Thibaut B. 2007a. Comparison of physical and mechanical properties of tension and opposite wood from ten tropical rainforest trees from different species. *Annals of Forest Science* **64:** 503–510.

Ruelle J, Clair B, Beauchêne J, Prévost MF, Fournier M. 2006. Tension wood and opposite wood in 21 tropical rain forest species. 2. Comparison of some anatomical and ultrastructural criteria. *IAWA Journal* **27:** 341–376.

Ruelle J, Yoshida M, Clair B, Thibaut B. 2007b. Peculiar tension wood structure in *Laetia procera* (Poepp.) Eichl. (Flacourtiaceae). *Trees* **21:** 345–355.

Samarakoon T. 2015. *Phylogenetic relationships of Samydaceae and taxonomic revision of the species of Casearia in South-Central Asia*. Dissertation, University of Southern Mississippi, USA.

Tippo O. 1946. The role of wood anatomy in phylogeny. *American Midland Naturalist* **36:** 362–372.

Xi Z, Ruhfel BR, Schaefer H, Amorim AM, Sugumaran M, Wurdack KJ, Endress PK, Matthews ML, Stevens PF, Mathews S, Davis CC, 2012. Phylogenomics and *a posteriori* data partitioning resolve the Cretaceous angiosperm radiation Malpighiales. *Proceedings of the National Academy of Sciences* **109:** 17519–17524.

Yoshinaga A, Kusumoto H, Laurans F, Pilate G, Takabe K. 2012. Lignification in poplar tension wood lignified cell wall layers. *Tree Physiology* **32:** 1129–1136.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Transverse sections of tension wood fibres observed with 3D laser scanning confocal microscopy. Scale bar = 10 µm. A, B, Lacistemataceae; C–S, Salicaceae *s.l.* A, *Lacistema pubescens*; B, *Lacistema* sp (thick S_2 layer); C, *Idesia polycarpa* (sampled in a naturally tilted tree); D, *Populus nigra* (*italica*); E, *P. trichocarpa*, F: *P. deltoides* × *nigra* (thick S_2 layer); G, *Salix myrsinifolia*; H, *S. purpurea* (thick S_2 layer); I, *Casearia commersoniana*; J, *C. grandiflora*; K, *C. guianensis*; L, *C. javitensis*; M, *C. pitumba*; N, *C. sylvestris*; O, *Homalium racemosum*; P, *Ryania speciosa* var. *bicolor*; Q, *Xylosma congesta*; R, *X. flexuosa*; S, *X. japonica*. A–H, one layer observed in the G-layer; I–R, more than two layers observed in the G-layer.