

PHYLOGENETIC RELATIONSHIPS WITHIN ARAUCARIACEAE BASED ON *rbcl* GENE SEQUENCES¹

HIROAKI SETOGUCHI,^{2,5,6} TAKESHI ASAKAWA OSAWA,³ JEAN-CHRISTOPHE PINTAUD,⁴ TANGUY JAFFRÉ,⁴ AND JEAN-MARIE VEILLON⁴

² Makino Herbarium, Faculty of Science, Tokyo Metropolitan University, Tokyo 192–03, Japan;

³ Department of Biology, Faculty of Science, Chiba University, Chiba 246, Japan; and

⁴ Department de Botanique, Centre ORSTOM de Nouméa, BP A5 Nouméa, New Caledonia

Phylogenetic relationships were determined in the Araucariaceae, which are now found mainly in the Southern Hemisphere. This conifer family was well diversified and widely distributed in both hemispheres during the Mesozoic era. The sequence of 1322 bases of the *rbcl* gene of cpDNA was determined from 29 species of Araucariaceae, representing almost all the species of the family. Phylogenetic trees determined by the parsimony method indicate that Araucariaceae are well defined by *rbcl* sequences and also that the monophyly of *Agathis* or *Araucaria* is well supported by high bootstrap values. The topology of these trees revealed that *Wollemia* had derived prior to *Agathis* and *Araucaria*. The *rbcl* phylogeny agrees well with the present recognition of four sections within *Araucaria*: *Araucaria*, *Bunya*, *Eutacta*, and *Intermedia*. Morphological characteristics of the number of cotyledons, position of male cone, and cuticular micromorphologies were evaluated as being phylogenetically informative. Section *Bunya* was found to be derived rather than to be the oldest taxon. Infrageneric relationships of *Agathis* could not be well elucidated because there are few informative site changes in the *rbcl* gene, suggesting the more recent differentiation of the species as their fossil records indicate. The New Caledonian *Araucaria* and *Agathis* species each formed a monophyletic group with very low differentiation in *rbcl* sequences among them, indicating rapid adaptive radiation to new edaphic conditions, i.e., ultramafic soils, in the post-Eocene era.

Key words: *Agathis*; *Araucaria*; Araucariaceae; Gondwana; *rbcl*; *Wollemia*.

From the biogeographical point of view, the Araucariaceae are one of the most interesting families with a primarily Southern Hemisphere distribution. They occur in South America, Australia, New Zealand, New Guinea, New Caledonia, and other South Pacific islands. The family consists of three well-defined genera, *Araucaria* de Jussieu (19 extant species sensu de Laubenfels [1972, 1988], *Agathis* Salisburi (13 species: Mabberley, 1987) and the monotypic genus *Wollemia* W. G. Jones, K. D. Hill and J. M. Allen. The first two genera have been recognized for more than a century; *Wollemia* was recently found in New South Wales, Australia, and de-

scribed in 1995. All species of *Araucaria* and most of *Agathis* species are restricted to the Southern Hemisphere. Some species of *Agathis* occur north of the equator in Malaysia, but this is regarded as a result of migration from the Southern Hemisphere to the Northwest during the Plio-Pleistocene (Florin, 1963). Thus, the extant species of the family are assumed to be of southern origin.

The genera *Araucaria* and *Agathis* each have distinctive morphological characteristics of leaves and cone elements (bract scale, ovuliferous scale, and seed), described before *Wollemia* was known. *Wollemia* shows intermediate characteristics between *Araucaria* and *Agathis* (Jones, Hill, and Allen, 1995), and similar characteristics are known only in fossil taxa such as *Podozamites* from the Jurassic to Tertiary Periods.

Araucaria is the most diversified genus in the family, being disjunctively distributed throughout the Southern Hemisphere (Chile, Argentina, southern Brazil, New Caledonia, Norfolk Island, Australia, and New Guinea). Although this distribution from a southern Pacific-Antarctic link to South America is generally taken as the result of a vicarious event and/or long-distance dispersal (Pole, 1994; Macphail, 1997), araucarian fossils have been widely excavated not only from the Southern but also the Northern Hemisphere. Further, they had been a major component of the Mesozoic forests (Miller, 1977; Stockey, 1982; Stockey, Nishida, and Nishida, 1992; Hill, 1995). Therefore, *Araucaria*'s present distribution might be considered as the relic type, although its extant species show a distribution pattern very similar to that of *Nothofagus* and other Gondwanan groups.

Fossils of *Araucaria* are among the oldest fossils of extant coniferous genera that have been found since the

¹ Manuscript received 26 August 1997; revision accepted 24 March 1998.

The authors thank Drs. G. J. Jordan and R. S. Hill (University of Tasmania), C. J. Quinn (The University of New South Wales), and G. Humphrey (The University of Sydney) for reviewing the manuscript; Mr. M. Bullet (Service de l'environnement à la Direction de l'Economie Rurale de la Province Sud, New Caledonia), Drs. M. Ono and M. Nakazawa (Tokyo Metropolitan University), S. Vodonaivalu (The University of the South Pacific, Fiji), A. Abraham (Singapore Botanic Gardens), M. Higuchi and T. Kitayama (National Science Museum), M. Tsuda (Kyoto University), M. Ito (Chiba University), H. Nishida (Chuou University, Japan), K. Ueda (Kanazawa University, Japan) for their cooperation in collecting plant materials and/or fruitful discussion; and N. Tanaka for helping with the analyses. This study was partly supported by Grant in Aid from Ministry of Education, Science and Culture Japan to H. S. (number 08740670) and T. A.-O. (number 0730457), Sasagawa Scientific Grant from Japan Science Society to T. A.-O., Grant in Aid for overseas research from Ministry of Education, Science and Culture Japan number 05041093 (Chief: M. Tsuda, Kyoto University) and number 08041135 (Chief: M. Ito, Chiba University).

⁵ Author for correspondence.

⁶ Current address: School of Natural Science, Faculty of Integrated Human Studies, Kyoto University, Yoshida, Nihonmatsu-machi, Kyoto 606-01, Japan (e-mail: seto@gaia.h.kyoto-u.ac.jp).



TABLE 1. The geological appearance, distribution, and extant species of five sections of *Araucaria*.

| | <i>Bunya</i> | <i>Yezonia</i> | Section <i>Intermedia</i> | <i>Araucaria</i> | <i>Eutacta</i> |
|-------------------------|------------------------------------|----------------|--------------------------------------|---|---|
| Earliest fossil record | Jurassic ^a | Cretaceous | late Cretaceous | Tertiary (or late Cretaceous) | Cretaceous (or Jurassic?) |
| Distribution of fossils | Europe Argentina | Northern Japan | New Zealand | Australia Argentina | Australia (and England?) |
| Extant species | <i>A. bidwillii</i> (Australia) | extinct | <i>A. hunsteinii</i> (New Guinea) | <i>A. araucana</i> <i>A. angustifolia</i> (South America) | <i>A. heterophylla</i> (Norfolk Island) <i>A. cunninghamii</i> (New Guinea) <i>A. bernieri</i> <i>A. biramulata</i> <i>A. columnaris</i> <i>A. humboldtensis</i> <i>A. laubenfelsii</i> <i>A. luxurians</i> <i>A. montana</i> <i>A. muelleri</i> <i>A. nemorosa</i> <i>A. rulei</i> <i>A. scopulorum</i> <i>A. schmidii</i> <i>A. subulata</i> (New Caledonia) |

^a See Discussion.

Triassic or Jurassic eras (Miller, 1977, 1988; Stockey, 1982). Before 1995, *Araucaria* had been infragenerically classified into four extant Sections: *Araucaria* (= *Columbea*), *Bunya*, *Eutacta*, and *Intermedia* (Wilde and Eames, 1952). In 1995, Ohsawa, Nishida, and Nishida (1995) added the new Section *Yezonia* to include the extinct species. This sectional classification was based on morphology: leaves, attachment of pollen cones and ovulate cones, cone-scale, vascular system cone-scale complex, type of seedling germination, and seedling. Fossil records and extant species within these sections are compared in Table 1. The oldest records of *Araucaria* fossils are those of the Sections *Bunya* and *Eutacta*; they were widespread across both hemispheres during the Jurassic (we are cautious in regard to the treatment of Triassic fossils as Hill [1995] recommended). In the other two extant sections, *Intermedia* and *Araucaria*, the distribution of both extant and extinct species is limited to the Southern Hemisphere (Australia, New Zealand, Tasmania, and Argentina), and their fossil records are relatively recent, starting with the late Cretaceous. Therefore, it is expected that Sections *Bunya* or *Eutacta* will be revealed to be the oldest in the genus *Araucaria* and will locate at the base of the phylogenetic tree of the extant species.

In contrast to that of the much-studied *Araucaria*, the classification of the *Agathis* remains somewhat controversial. In his revision of the entire genus, Whitmore (1980) recognized 13 species based mainly on characteristics of the male cones; *Agathis vitiensis* (from Fiji) and *A. obtusa* (from Vanuatu) were reduced to synonymy with *A. macrophylla* (cf. Whitmore, 1977). However, the species *A. vitiensis* is still recognized in local flora as being distinctive from others (e.g., Smith, 1981). de Laubenfels (1988) recognized 21 species, but his treatment has not gained acceptance. Although infrageneric classification has been proposed by both authors, the morphological differences among groups or sections are very

minute compared to those in the infrageneric classification of *Araucaria*.

The highest concentration of specific diversity of Araucariaceae is in New Caledonia. In spite of its small area (19 000 km²), New Caledonia possesses a very rich and distinctive flora (Jaffré, 1995). This is especially true in the case of the Araucariaceae: 13 of the 19 species of *Araucaria* and five of the 13 species of *Agathis* are endemic to this island and are well diversified in their morphological characteristics (e.g., de Laubenfels, 1972; Veillon, 1978, 1980). Thus in the phylogenetic study of the Araucariaceae, it is indispensable to include all or many New Caledonian species.

This study aims to construct a sequence database for the chloroplast encoded *rbcL* gene in order to reconstruct a molecular phylogeny for the family and to use this phylogeny to address the following questions: (1) Are the three genera of Araucariaceae supported? (2) What is the relationship among *Wollemia*, *Araucaria*, and *Agathis*? (3) Is the infrageneric classification of *Araucaria* supported? (4) Which section is located in the basal cluster within *Araucaria*? (5) What phylogenetic relationships are observed among species of *Araucaria* and *Agathis* in New Caledonia?

MATERIALS AND METHODS

Material—Plant material was collected from natural habitats or cultivated plantings, dried and preserved in silica gel. In total, 29 species were selected representing all species of *Araucaria* (19 species) sensu de Laubenfels (1972, 1988), and ten species of *Agathis*. The *rbcL* sequence of *Wollemia nobilis* was referenced from GenBank. Materials and collection/source data are listed in Table 2.

Total DNA extraction—Dry samples were frozen using liquid nitrogen and pulverized to a fine powder. Before the DNA extraction, leaf powder was suspended in HEPES buffer (pH 8.0) and centrifuged at 10 000 rpm and 20°C for 5 min to remove the sticky polysaccharide

TABLE 2. Taxa compared for *rbcL* sequence variation and collection/source data.

| Species | Collection data/source [cultivation no.] | GenBank accession number |
|---|---|-----------------------------|
| Genus <i>Araucaria</i> | | |
| <i>A. angustifolia</i> (Bertol.) Kuntze | Cultivated in Botanical Garden, Universidad Austral de Chile, Chile: Nakazawa and Ono s.n. | GBANU96470 |
| <i>A. araucana</i> (Molina) K.Koch | Cultivated in Botanical Garden, Universidad Austral de Chile, Chile: Nakazawa and Ono s.n. | GBANU96467 |
| <i>A. bernieri</i> Buchholz | New Caledonia: Setoguchi NC95060 (MAK) | GBANU96460 |
| <i>A. bidwillii</i> Hook. | New South Wales, Australia: Setoguchi AUS023 (MAK) | GBANU96472 |
| <i>A. biramulata</i> Buchholz | New Caledonia: Setoguchi NC95019 (MAK) | GBANU96475 |
| <i>A. columnaris</i> (G.Forst.) Hook. | New Caledonia: Setoguchi NC95016 (MAK) | GBANU96461 |
| <i>A. cunninghamii</i> Aiton ex D.Don | Cultivated in Singapore Botanic Garden [no cultivated number]; Seto- guchi s.n. | GBANU96469 |
| <i>A. heterophylla</i> (Salisb.) Franco | Norfolk Island: J.-C. Pintaud 381 (MAK) | GBANU96462 |
| <i>A. humboldtensis</i> Buchholz | New Caledonia: Setoguchi NC95077 (MAK) | GBANU96471 |
| <i>A. hunsteinii</i> K. Schum. | Cultivated in Singapore Botanic Garden [B-26]; Setoguchi s.n. | GBANU96468 |
| <i>A. laubenfelsii</i> Corbasson | New Caledonia: Setoguchi NC95014 (MAK) | GBANU96463 |
| <i>A. luxurians</i> (Brongn. et Gris) de Laub. | New Caledonia: Setoguchi NC95058 (MAK) | GBANU96464 |
| <i>A. montana</i> Brongn. et Gris | New Caledonia: Setoguchi NC95090 (MAK) | GBANU96457 |
| <i>A. muelleri</i> (Carriere) Bongn. et Gris | New Caledonia: J.-C. Pintaud no number (MAK) | GBANU96465 |
| <i>A. nemorosa</i> de Laub. | New Caledonia: J.-C. Pintaud 471 (MAK) | GBANU96458 |
| <i>A. rulei</i> F. Muell. | New Caledonia: T. Jaffré 3265 (NOU) | GBANU96466 |
| <i>A. schmidii</i> de Laub. | New Caledonia: J.-C. Pintaud 466 (MAK) | GBANU96473 |
| <i>A. scopulorum</i> de Laub. | New Caledonia: Setoguchi NC95086 (MAK) | GBANU96459 |
| <i>A. subulata</i> Vieill. | New Caledonia: Setoguchi NC97009 (MAK) | GBANU96474 |
| Genus <i>Agathis</i> | | |
| <i>A. borneensis</i> Warb. | Cultivated in Singapore Botanic Garden [XG-17]; Setoguchi s.n. | GBANU96476 |
| <i>A. dammara</i> (Lamb.) Rich. | Cultivated in Bogor Botanical Garden [V.F8-A]; Setoguchi s.n. | GBANU96477 |
| <i>A. lanceolata</i> Lindl. ex Warb. | New Caledonia: Setoguchi NC93082 (MAK) | GBANU96481 |
| <i>A. montana</i> de Laub. | New Caledonia: J.-C. Pintaud 467 (MAK) | GBANU96478 |
| <i>A. moorei</i> (Lindl.) Mast. | New Caledonia: Setoguchi NC95059 (MAK) | GBANU96480 |
| <i>A. obtusa</i> Mast. | Cultivated in Bogor Botanical Garden [V.F7]; Setoguchi s.n. | GBANU96482 |
| <i>A. ovata</i> (Moore) Warb. | New Caledonia: Setoguchi NC95061 (MAK) | GBANU96483 |
| <i>A. palmerstoni</i> F. Muell. | Cultivated in Bogor Botanical Garden [V.F58]; Setoguchi s.n. | GBANU96479 |
| <i>A. robusta</i> (C.Moore ex F.Muell.) F.M.Bailey | Cultivated in Pamplermouses Botanical Garden, Mauritius, Ohsawa no number (MAK) | GBANU96484 |
| <i>A. vitiensis</i> Benth. et Hook. f. ex Drake | Fiji Islands: Setoguchi F95027 (MAK) | GBANU96485 |
| Genus <i>Wollemia</i> | | |
| <i>W. nobilis</i> E.G.Jones, K.D.Hill and J.M.Allen | (referenced GenBank) | GBANU87757 |

(Setoguchi and Ohba, 1995). Total DNA was isolated from the collected pellet using the CTAB method of Hasebe and Iwatsuki (1990).

Amplification and sequencing of the *rbcL* gene of cpDNA—The double-stranded DNA of most of the *rbcL* gene of cpDNA, ~1350 bp, was amplified by 30 cycles of symmetric polymerase chain reaction (PCR) as shown by use of primers aF and cR of Hasebe et al. (1994) for *rbcL*. PCR cycle conditions in the first cycle consisted of 2 min at 94°C for denaturation, 1 min at 45°C for primer annealing, and 1 min at 72°C for primer extension. Denaturation time at 94°C was reduced to 1 min during the next 28 cycles. The time at 72°C was increased to 5 min in the last cycle. PCR products were purified by electrophoresis in 1.0% agarose gel using 1 × TAE buffer. The gel was stained with ethidium bromide and the DNA was eluted using GeneClean II (Bio 101, Vista, California, USA). Purified DNAs were sequenced in both directions by the standard methods of the Taq dye deoxy terminator cycle sequencing kit (Perkin Elmer, Foster City, California, USA) on an Applied Biosystems Model 373A automated sequencer (Applied Biosystems, Foster City, California, USA). Primers for this sequence determination were aF, cF, cR, bR, and cR of Hasebe et al. (1994) and originally designed primers ARGbF, ARGsF, and ARGsR. The sequences of these original primers are as follows: ARGbF, 5'-TACCCCTTA-GACCTTTTGAAGAAGGTTTC; ARGsF, 5'-ACTGTACTAGGTA AACTTGAAGGTGAACG; ARGsR, 5'-GAACCTTCTCAAAA-

AGGTCTAAGGGGTA. Sequence data were aligned manually with the GENETYX program (The Software Development Co., Tokyo, Japan).

Outgroup—Before the phylogenetic analysis of the Araucariaceae, we examined the phylogenetic position of Araucariaceae among conifers in order to select the outgroup to Araucariaceae. Following Chase et al. (1993), we used the *rbcL* sequences of 20 coniferous taxa and *Ginkgo* (as an outgroup), which were registered in GenBank, along with several species of Araucariaceae. As a result, a cluster of Cupressaceae, Podocarpaceae, and Taxodiaceae formed the sister group to Araucariaceae, and we used the *rbcL* sequences of *Juniperus conferta* (GBANL12573: Cupressaceae), *Taxodium distichum* (GBANS75127: Taxodiaceae), and *Podocarpus gracilior* (GBANX58135: Podocarpaceae) to root phylogenetic trees of Araucariaceae.

Phylogenetic analysis—A database of 1322 bp of the *rbcL* gene was used for the phylogenetic analyses. For the present study, *rbcL* gene sequence (positions 28–1350) were phylogenetically analyzed using PAUP (Phylogenetic Analysis Using Parsimony) version 3.1.1 (Swofford, 1993). We performed the heuristic search under the equal weighting criteria using Tree Bisection Reconnection (TBR) branch-swapping algorithm with MULPARS on, Steepest Descent on, and 100 replicates of random taxon addition. Accelerated transformation (ACCTRAN) was used for optimization in the analyses. We used the bootstrap analysis

TABLE 3. Pairwise distances between species of Araucariaceae and three outgroups. Below diagonal shows absolute distances, and above diagonal shows mean distances.

| Species | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|-----------------------------------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1 <i>Agathis borneensis</i> | | 0.005 | 0.005 | 0.005 | 0.006 | 0.007 | 0.007 | 0.007 | 0.007 | 0.008 | 0.028 | 0.028 | 0.028 | 0.029 |
| 2 <i>Agathis damnara</i> | 7 | — | 0.005 | 0.005 | 0.004 | 0.003 | 0.002 | 0.003 | 0.002 | 0.003 | 0.026 | 0.026 | 0.026 | 0.026 |
| 3 <i>Agathis montana</i> | 7 | 6 | — | 0.004 | 0.001 | 0.002 | 0.005 | 0.002 | 0.005 | 0.005 | 0.024 | 0.024 | 0.024 | 0.025 |
| 4 <i>Agathis palmerstoni</i> | 6 | 7 | 5 | — | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.006 | 0.026 | 0.026 | 0.026 | 0.027 |
| 5 <i>Agathis moorei</i> | 8 | 5 | 1 | 6 | — | 0.001 | 0.004 | 0.001 | 0.004 | 0.005 | 0.025 | 0.025 | 0.025 | 0.026 |
| 6 <i>Agathis lanceolata</i> | 9 | 4 | 2 | 7 | 1 | — | 0.003 | 0.000 | 0.003 | 0.004 | 0.024 | 0.024 | 0.024 | 0.025 |
| 7 <i>Agathis obtusa</i> | 9 | 3 | 6 | 7 | 5 | 4 | — | 0.003 | 0.000 | 0.001 | 0.026 | 0.026 | 0.026 | 0.026 |
| 8 <i>Agathis ovata</i> | 9 | 4 | 2 | 7 | 1 | 0 | 4 | — | 0.003 | 0.004 | 0.024 | 0.024 | 0.024 | 0.025 |
| 9 <i>Agathis robusta</i> | 9 | 3 | 6 | 7 | 5 | 4 | 0 | 4 | — | 0.001 | 0.026 | 0.026 | 0.026 | 0.026 |
| 10 <i>Agathis vittensis</i> | 10 | 4 | 7 | 8 | 6 | 5 | 1 | 5 | 1 | — | 0.026 | 0.026 | 0.026 | 0.027 |
| 11 <i>Araucaria montana</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | — | 0.000 | 0.000 | 0.001 |
| 12 <i>Araucaria nemorosa</i> | 7 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | — | 0.000 | 0.001 |
| 13 <i>Araucaria scopulorum</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | — | 0.001 |
| 14 <i>Araucaria bernieri</i> | 38 | 35 | 33 | 36 | 34 | 33 | 35 | 33 | 35 | 36 | 1 | 1 | 1 | — |
| 15 <i>Araucaria columnaris</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 16 <i>Araucaria heterophylla</i> | 36 | 33 | 33 | 36 | 32 | 33 | 35 | 33 | 35 | 36 | 7 | 7 | 7 | 8 |
| 17 <i>Araucaria laubenfelsii</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 18 <i>Araucaria luxurians</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 19 <i>Araucaria muelleri</i> | 40 | 37 | 35 | 38 | 36 | 35 | 37 | 35 | 37 | 38 | 3 | 3 | 3 | 4 |
| 20 <i>Araucaria rulei</i> | 42 | 39 | 37 | 40 | 38 | 37 | 39 | 37 | 39 | 40 | 5 | 5 | 5 | 6 |
| 21 <i>Araucaria araucana</i> | 33 | 32 | 29 | 31 | 30 | 31 | 32 | 31 | 32 | 33 | 17 | 17 | 17 | 18 |
| 22 <i>Araucaria hunsteinii</i> | 34 | 29 | 30 | 30 | 29 | 28 | 29 | 28 | 29 | 30 | 16 | 16 | 16 | 17 |
| 23 <i>Araucaria cunninghamii</i> | 40 | 35 | 38 | 40 | 37 | 36 | 37 | 36 | 37 | 38 | 14 | 14 | 14 | 15 |
| 24 <i>Araucaria angustifolia</i> | 32 | 29 | 28 | 30 | 29 | 28 | 29 | 28 | 29 | 30 | 16 | 16 | 16 | 17 |
| 25 <i>Araucaria humboldtensis</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 26 <i>Araucaria bidwillii</i> | 36 | 31 | 32 | 32 | 31 | 30 | 31 | 30 | 31 | 32 | 16 | 16 | 16 | 17 |
| 27 <i>Araucaria schmidii</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 28 <i>Araucaria subulata</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 29 <i>Araucaria biramulata</i> | 37 | 34 | 32 | 35 | 33 | 32 | 34 | 32 | 34 | 35 | 0 | 0 | 0 | 1 |
| 30 <i>Wollemia nobilis</i> | 27 | 24 | 22 | 23 | 21 | 22 | 24 | 22 | 24 | 25 | 21 | 21 | 21 | 22 |
| 31 <i>Podocarpus</i> | 119 | 116 | 116 | 115 | 115 | 116 | 116 | 116 | 116 | 117 | 113 | 113 | 113 | 114 |
| 32 <i>Juniperus</i> | 115 | 113 | 113 | 112 | 112 | 113 | 113 | 113 | 113 | 114 | 111 | 111 | 111 | 112 |
| 33 <i>Taxodium</i> | 113 | 112 | 110 | 111 | 111 | 112 | 112 | 112 | 112 | 113 | 107 | 107 | 107 | 108 |

(Felsenstein, 1985; Felsenstein and Kishino, 1993) of 1000 replicates by the heuristic search under unweighted criteria to assess the internal support for clades. Character state reconstructions were performed using MacClade, version 3.05 (Maddison and Maddison, 1992). All character changes were treated as unrooted, equally weighted, and were resolved using two ways of optimization: accelerated transformation (ACCTRAN) and delayed transformation (DELTRAN).

RESULTS

Sequences for 29 species were obtained and deposited in GenBank (Table 2). Pairwise distances between taxa are listed in Table 3. Values of pairwise percentage sequence divergence ranged from 0 to 1.7% among *Araucaria* species, from 0 to 0.8% among *Agathis* species, from 2.1 to 3.2% between *Araucaria* and *Agathis* species, from 1.3 to 2.0% between *Wollemia* and *Araucaria* species, from 1.6 to 2.0% between *Wollemia* and *Agathis* species, and from 7.4 to 9.0% between Araucariaceae and outgroup taxa. In particular, the values were very low among New Caledonian *Araucaria* and *Agathis* species, between 0 and 0.5% and between 0.1 and 0.2%, respectively (Table 3).

Parsimony analysis resulted in 20 most-parsimonious trees of 281 steps with a Consistency Index of 0.766 (excluding uninformative characters) and a Retention Index of 0.925 under the equal weighting criterion. The strict consensus tree is shown in Fig. 1 with bootstrap values. Furthermore, the topology supported by 50% majority

consensus is shown by dotted lines. The topology of the 20 trees was unaltered when Albert's weightings (Albert, Chase, and Mishler, 1993) were substituted.

Relationships between *Araucaria*, *Agathis* and *Wollemia*—The Araucariaceae are well defined by the *rbcL* sequence, and its monophyly is supported to 100% in bootstrap value. The topology of these trees reveals that *Wollemia* derived first and then *Agathis* and *Araucaria*. The monophyly of *Agathis* or *Araucaria* is well supported by high bootstrap values in each search (100 and 89%, respectively).

Phylogeny within *Araucaria*—The phylogeny of *Araucaria* is relatively well resolved in the present phylogenetic analysis. The phylogenetic trees divided into two clades at first: one clade consists of all 15 species of Section *Eutacta* and another consists of the remaining sections, *Araucaria*, *Bunya*, and *Intermedia*. In the former clade, *Araucaria cunninghamii* (distributed in Australia and New Guinea) was derived first, and after that, *A. heterophylla* (from Norfolk Island). The 13 endemics of New Caledonia formed a monophyletic group. The homology of *rbcL* sequences among New Caledonian species is very high, between 99.5 and 100% (Table 3). The sequence in ten of the 13 endemics (*Araucaria biramulata*, *A. columnaris*, *A. humboldtensis*, *A. lauben-*

TABLE 3. Extended.

| 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.028 | 0.027 | 0.028 | 0.028 | 0.030 | 0.032 | 0.025 | 0.026 | 0.030 | 0.024 | 0.028 | 0.027 | 0.028 | 0.028 | 0.028 | 0.020 | 0.090 | 0.087 | 0.085 |
| 0.026 | 0.025 | 0.026 | 0.026 | 0.028 | 0.030 | 0.024 | 0.022 | 0.026 | 0.022 | 0.026 | 0.023 | 0.026 | 0.026 | 0.026 | 0.018 | 0.088 | 0.085 | 0.085 |
| 0.024 | 0.025 | 0.024 | 0.024 | 0.026 | 0.028 | 0.022 | 0.023 | 0.029 | 0.021 | 0.024 | 0.024 | 0.024 | 0.024 | 0.024 | 0.017 | 0.088 | 0.085 | 0.083 |
| 0.026 | 0.027 | 0.026 | 0.026 | 0.029 | 0.030 | 0.023 | 0.023 | 0.030 | 0.023 | 0.026 | 0.024 | 0.026 | 0.026 | 0.026 | 0.017 | 0.087 | 0.085 | 0.084 |
| 0.025 | 0.024 | 0.025 | 0.025 | 0.027 | 0.029 | 0.023 | 0.022 | 0.028 | 0.022 | 0.025 | 0.023 | 0.025 | 0.025 | 0.025 | 0.016 | 0.087 | 0.085 | 0.084 |
| 0.024 | 0.025 | 0.024 | 0.024 | 0.026 | 0.028 | 0.023 | 0.021 | 0.027 | 0.021 | 0.024 | 0.023 | 0.024 | 0.024 | 0.024 | 0.017 | 0.088 | 0.085 | 0.085 |
| 0.026 | 0.026 | 0.026 | 0.026 | 0.028 | 0.030 | 0.024 | 0.022 | 0.028 | 0.022 | 0.026 | 0.023 | 0.026 | 0.026 | 0.026 | 0.018 | 0.088 | 0.085 | 0.085 |
| 0.024 | 0.025 | 0.024 | 0.024 | 0.026 | 0.028 | 0.023 | 0.021 | 0.027 | 0.021 | 0.024 | 0.023 | 0.024 | 0.024 | 0.024 | 0.017 | 0.088 | 0.085 | 0.085 |
| 0.026 | 0.026 | 0.026 | 0.026 | 0.028 | 0.030 | 0.024 | 0.022 | 0.028 | 0.022 | 0.026 | 0.023 | 0.026 | 0.026 | 0.026 | 0.018 | 0.088 | 0.085 | 0.085 |
| 0.026 | 0.027 | 0.026 | 0.026 | 0.029 | 0.030 | 0.025 | 0.023 | 0.029 | 0.023 | 0.026 | 0.024 | 0.026 | 0.026 | 0.026 | 0.019 | 0.089 | 0.086 | 0.085 |
| 0.000 | 0.005 | 0.000 | 0.000 | 0.002 | 0.004 | 0.013 | 0.012 | 0.011 | 0.012 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 0.000 | 0.005 | 0.000 | 0.000 | 0.002 | 0.004 | 0.013 | 0.012 | 0.011 | 0.012 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 0.000 | 0.005 | 0.000 | 0.000 | 0.002 | 0.004 | 0.013 | 0.012 | 0.011 | 0.012 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 0.001 | 0.006 | 0.001 | 0.001 | 0.003 | 0.005 | 0.014 | 0.013 | 0.011 | 0.013 | 0.001 | 0.013 | 0.001 | 0.001 | 0.001 | 0.017 | 0.086 | 0.085 | 0.082 |
| — | 0.005 | 0.000 | 0.000 | 0.002 | 0.004 | 0.013 | 0.012 | 0.011 | 0.012 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 7 | — | 0.005 | 0.005 | 0.008 | 0.009 | 0.014 | 0.013 | 0.010 | 0.014 | 0.005 | 0.013 | 0.005 | 0.005 | 0.005 | 0.015 | 0.085 | 0.083 | 0.082 |
| 0 | 7 | — | 0.000 | 0.002 | 0.004 | 0.013 | 0.012 | 0.011 | 0.012 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 0 | 7 | 0 | — | 0.002 | 0.004 | 0.013 | 0.012 | 0.011 | 0.012 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 3 | 10 | 3 | 3 | — | 0.003 | 0.015 | 0.014 | 0.013 | 0.014 | 0.002 | 0.014 | 0.002 | 0.002 | 0.002 | 0.018 | 0.088 | 0.085 | 0.082 |
| 5 | 12 | 5 | 5 | 4 | — | 0.017 | 0.016 | 0.014 | 0.016 | 0.004 | 0.016 | 0.004 | 0.004 | 0.004 | 0.020 | 0.089 | 0.087 | 0.084 |
| 17 | 18 | 17 | 17 | 20 | 22 | — | 0.008 | 0.016 | 0.002 | 0.013 | 0.010 | 0.013 | 0.013 | 0.013 | 0.015 | 0.079 | 0.078 | 0.075 |
| 16 | 17 | 16 | 16 | 19 | 21 | 11 | — | 0.015 | 0.008 | 0.012 | 0.002 | 0.012 | 0.012 | 0.012 | 0.013 | 0.081 | 0.082 | 0.082 |
| 14 | 13 | 14 | 14 | 17 | 19 | 21 | 20 | — | 0.015 | 0.011 | 0.015 | 0.011 | 0.011 | 0.011 | 0.019 | 0.088 | 0.086 | 0.085 |
| 16 | 19 | 16 | 16 | 19 | 21 | 3 | 10 | 20 | — | 0.012 | 0.009 | 0.012 | 0.012 | 0.012 | 0.014 | 0.081 | 0.079 | 0.076 |
| 0 | 7 | 0 | 0 | 3 | 5 | 17 | 6 | 14 | 16 | — | 0.012 | 0.000 | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 16 | 17 | 16 | 16 | 19 | 21 | 13 | 2 | 20 | 12 | 16 | — | 0.012 | 0.012 | 0.012 | 0.014 | 0.082 | 0.082 | 0.082 |
| 0 | 7 | 0 | 0 | 3 | 5 | 17 | 16 | 14 | 16 | 0 | 16 | — | 0.000 | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 0 | 7 | 0 | 0 | 3 | 5 | 17 | 16 | 14 | 16 | 0 | 16 | 0 | — | 0.000 | 0.016 | 0.085 | 0.084 | 0.081 |
| 0 | 7 | 0 | 0 | 3 | 5 | 17 | 16 | 14 | 16 | 0 | 16 | 0 | 0 | — | 0.016 | 0.085 | 0.084 | 0.081 |
| 21 | 20 | 21 | 21 | 24 | 26 | 20 | 17 | 25 | 19 | 21 | 19 | 21 | 21 | 21 | — | 0.078 | 0.074 | 0.076 |
| 113 | 112 | 113 | 113 | 116 | 118 | 105 | 107 | 116 | 107 | 113 | 109 | 113 | 113 | 113 | 103 | — | 0.084 | 0.093 |
| 111 | 110 | 111 | 111 | 113 | 115 | 103 | 108 | 114 | 104 | 111 | 109 | 111 | 111 | 111 | 98 | 111 | — | 0.039 |
| 107 | 108 | 107 | 107 | 109 | 111 | 99 | 108 | 112 | 100 | 107 | 109 | 107 | 107 | 107 | 100 | 123 | 51 | — |

felsii, *A. luxurians*, *A. montana*, *A. nemorosa*, *A. schmidii*, *A. scopulorum*, and *A. subulata*) was identical.

The second major clade in *Araucaria* further divided into two clades, one cluster consists of two South American species of Section *Araucaria* (*A. araucana* and *A. angustifolia*), and of New Guinean species of Section *Intermedia* (*A. humsteinii*) and Australian species of Section *Bunya* (*A. bidwillii*).

Phylogeny within *Agathis*—Unlike *Araucaria*, the *rbcl* sequences resolved the relationships in *Agathis* poorly. In the strict consensus tree (Fig. 1), only two monophyletic groups were present: one of *Agathis borneensis* and *A. palmerstonii* (distributed in South East Asia) and another of *A. obtusa* (Vanuatu), *A. robusta* (Australia), and *A. vitiensis* (the Fiji Islands). The 50% majority rule consensus suggested a closer relationship between all four endemics to New Caledonia, and also a relationship between *A. dammara* (distributed in Malaysian region), *A. obtusa*, *A. robusta*, and *A. vitiensis*, but there is no support for these clusters in the data (bootstrap value <50%).

DISCUSSION

In this study, the *rbcl* sequence data set indicates that the Araucariaceae are a highly coherent taxon and that the monophyly of the genera *Araucaria* and *Agathis* is well supported.

Phylogenetic position of *Wollemia*—In the phylogenetic tree, the genus *Wollemia* is derived before the divergence of *Araucaria* and *Agathis*. Based on the topology, *Wollemia* can be interpreted as the earliest diverged genus in Araucariaceae. *Wollemia* shares morphologies among *Araucaria* and *Agathis* (Jones, Hill, and Allen, 1995). Morphological characteristics shared by both *Wollemia* and *Araucaria* (i.e., closely crowned sessile and amphistomatic leaves, aristate bract scales) or *Wollemia* and *Agathis* (i.e., fully fused bract and ovuliferous scale, winged seed) are interpreted as plesiomorphic characters in the family. To examine this theory, further knowledge is needed, especially on the comparative morphology of *Wollemia* and related fossil taxa, for understanding the relationships among *Wollemia*, *Araucaria* and *Agathis*.

Infrageneric relationships of *Araucaria*—The *rbcl* phylogeny agrees well with the present infrageneric classification system, which recognizes four sections of extant species: *Araucaria*, *Bunya*, *Eutacta*, and *Intermedia*. The classification is based on the combination of morphological characteristics, such as leaf shape, stomatal distribution and orientation, polar extension, position of male cone, number of vascular supplies to cone scale and their arrangement, dehiscence of cone scale, number of cotyledons, and germination manner (Wilde and Eames, 1952; Stockey, 1982; Stockey and Ko, 1986). Therefore, most of these morphological characteristics well reflect

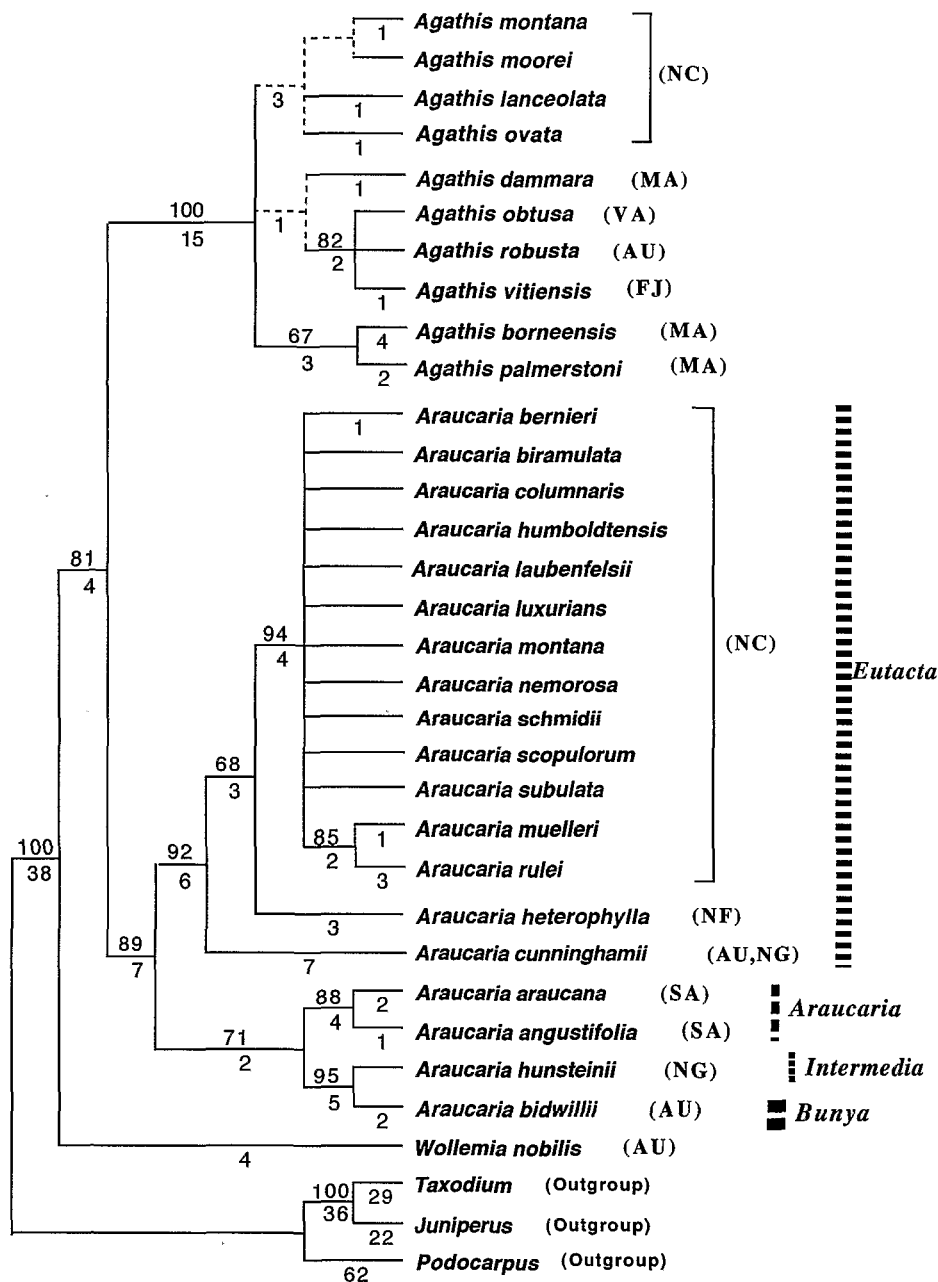


Fig. 1. Consensus tree of the 20 equally parsimonious ones for Araucariaceae based on cpDNA *rbcL* sequences, showing the clades that are supported in the strict consensus by solid lines and the clades that collapse by dotted ones. Length = 281 steps, CI = 0.766 (excluding uninformative data), RI = 0.925. A percentage of the 1000 bootstrap values (>50%) is given for each node. Distribution area for each species is indicated within parentheses. Sectional attribute for each species is indicated by a dashed line. Figure abbreviations: AU = Australia, FJ = Fiji, MA = Malaysian region, NC = New Caledonia, NF = Norfolk Island, NG = New Guinea, NZ = New Zealand, SA = South America, VA = Vanuatu.

the phylogenetic relationships of the genus. In particular, the major branching of the *rbcL* phylogeny in *Araucaria*, which splits Section *Eutacta* from the other sections, corresponded to the number of cotyledons (four in Section *Eutacta* and two in other sections), position of male cone (terminal in Section *Eutacta* and axillary in other sections), stomatal orientation to long axis of leaf (mostly oblique or perpendicular in Section *Eutacta* and mostly parallel in other sections), and stomatal distribution (mostly two bands or groups in Section *Eutacta* and discontinuous rows in other sections). These morphological

characteristics should be evaluated as being phylogenetically informative and will be pertinent to estimating the phylogenetic position of extinct species of *Araucaria*.

We further polarized the morphological characteristics discussed above (Figs. 2–6). Figure 2 shows the evolutionary trend in the number of cotyledons. Cotyledons of *Araucaria* vary in number as discussed above, but all species of *Agathis* and *Wollemia* have two (de Laubenfels, 1972, 1988; Whitmore, 1980; Jones, Hill, and Allen, 1995). ACCTRAN and DELTRAN without outgroups showed the same distribution and evolutionary trends of

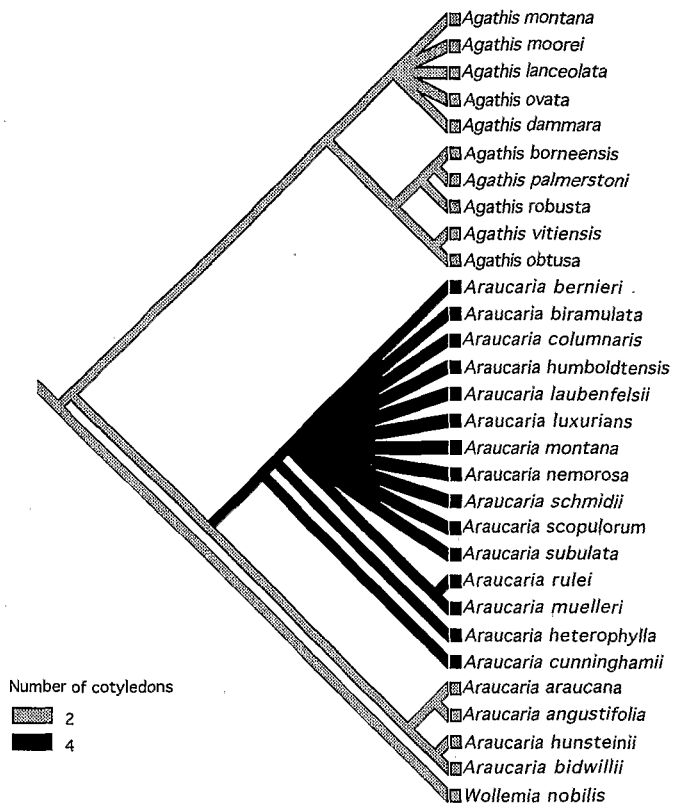


Fig. 2. Parsimonious replacement of characters of the number of cotyledons with ACCTTRAN and DELTRAN optimization on the most parsimonious phylogenetic tree based on the *rbcL* gene sequences (Fig. 1). There is no difference in the character distribution between ACCTTRAN and DELTRAN optimization.

these characters. Parsimony evaluated the plesiomorphy as two both in *Araucaria* and Araucariaceae. This fact agrees well with palaeobotanical data since all araucarian fossil species from the Mesozoic have dicotyledonous embryos (Stockey, 1975, 1978, 1980a, b; Stockey, Nishida, and Nishida, 1992). An increase from two to four cotyledons occurred once at the level of the common ancestor of section *Eutacta*.

Figure 3 shows the evolutionary trend in position of male cone, which is terminated in *Wollemia* (Jones, Hill, and Allen, 1995) and axillary in *Agathis* (Whitmore, 1980). Parsimonious replacement of the character indicates that the plesiomorphic state cannot be determined in either *Araucaria* or the Araucariaceae. A shift from terminal to axillary or from axillary to terminal occurred more than once in the family. The position of the male cone in the fossil record is needed to interpret more about the evolutionary trend.

Figure 4 shows the evolutionary trend in stomatal orientation. Stomata of *Agathis* are obliquely and/or perpendicularly oriented to the long axis of the leaf (Stockey and Atkinson, 1993) and those of *Wollemia* have not been observed. ACCTTRAN and DELTRAN evaluated the plesiomorphy as being oblique and/or perpendicular in *Araucaria*. Parallel orientation arose in the ancestor of sections *Araucaria*, *Bunya*, and *Intermedia*. It has been difficult to assess the placement of the leaves in any extant section because of bad preservation of leaf cuticles

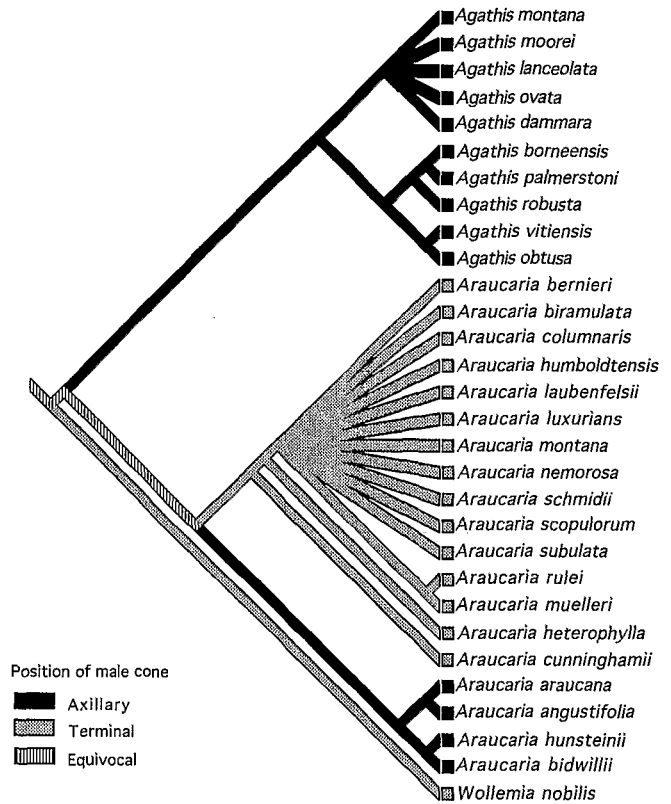


Fig. 3. Parsimonious replacement of the position of the male cone with ACCTTRAN and DELTRAN optimization on the most parsimonious phylogenetic tree based on the *rbcL* gene sequences (Fig. 1). There is no difference in the character distribution between ACCTTRAN and DELTRAN optimization.

in Mesozoic fossil leaves (Stockey, 1994). Therefore, further details of micromorphology of fossil *Araucaria* and cuticle micromorphology in *Wollemia* are needed to determine the evolutionary trends in this character in the family.

Figure 5 shows the evolutionary trend of stomatal distribution. Stomata of *Agathis* occur in discontinuous rows (Stockey and Atkinson, 1993), and those of *Wollemia* are unknown. ACCTTRAN and DELTRAN evaluated the plesiomorphy of the stomatal distribution as occurring in discontinuous rows in *Araucaria*. A shift from discontinuous rows to two bands appears to have occurred once in the ancestor of section *Eutacta*, with reversal among New Caledonian *Araucaria*.

Phylogenetic position of the Section *Bunya* in the genus *Araucaria*—Before we obtained the *rbcL* phylogeny of Araucariaceae, we expected that *Araucaria bidwillii* of Section *Bunya* would be placed at the bottom of the phylogenetic tree of *Araucaria* since Section *Bunya* is one of the oldest recorded sections from the Jurassic (Wieland, 1935; Calder, 1953; Stockey, 1975, 1978). However, the molecular data do not support the early divergence of Section *Bunya*, because *A. bidwillii* was found to be located in the terminal cluster together with *A. hunsteinii*.

Several palaeobotanical works have already pointed out the differences between *Araucaria bidwillii* and the

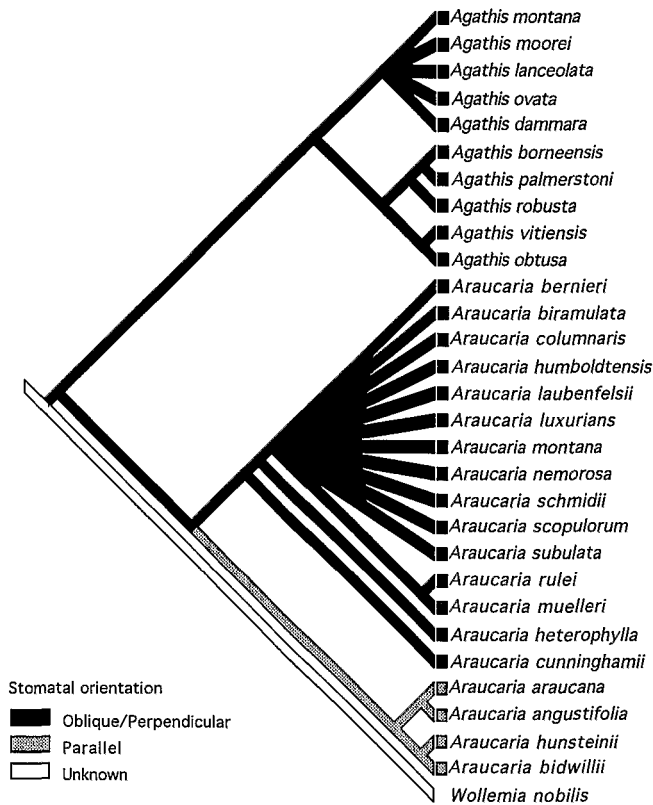


Fig. 4. Parsimonious replacement of stomatal orientation with ACCTRAN and DELTRAN optimization on the most parsimonious phylogenetic tree based on the *rbcL* gene sequences (Fig. 1). There is no difference in the character distribution between ACCTRAN and DELTRAN optimization.

fossil species assigned to Section *Bunya* in seed size and seedling anatomy. The seed size of *A. bidwillii* is large, 5–6 cm in length and 2.5–3.5 cm in width (Burrows, Boag, and Stockey, 1992) compared with 0.8–1.3 cm in length and 0.2–0.6 cm in width in *A. mirabilis* from Argentina (Stockey, 1975, 1978), 0.8 cm in length and 0.3 cm in width in *A. brownii* from the UK (Stockey, 1980a), 1.6 cm in length and 0.7 cm in width in *A. sphaerocarpa* from the UK (Stockey, 1980b). Seed size is also small in all other fossil species, such as *A. nihongii* (Stockey, Nishida, and Nishida, 1992) or *A. nipponensis* (Stockey, Nishida, and Nishida, 1994). Burrows, Boag, and Stockey (1992) indicated that seeds of extinct species were too small for cryptogeal (hypogeal) germination, and Stockey (1994) even suggested that hypogeal germination was a relatively recent phenomenon in the Araucariaceae. Thus it is suggested that epigeal germination is the general condition (plesiomorphy) within Section *Bunya*.

Stockey, Nishida, and Nishida (1990), Burrows, Boag, and Stockey (1992), and Burrows and Stockey (1994) showed that seedlings of *Araucaria bidwillii* develop concentric rings of vascular tissue between shoot apex and hypocotyl, but such a structure is not present in the fossil seedlings.

The present finding on the phylogenetic position of *Araucaria bidwillii* is consistent with these paleobotanical data. We conclude that the Mesozoic araucarians assigned to Section *Bunya*, which were distributed in both

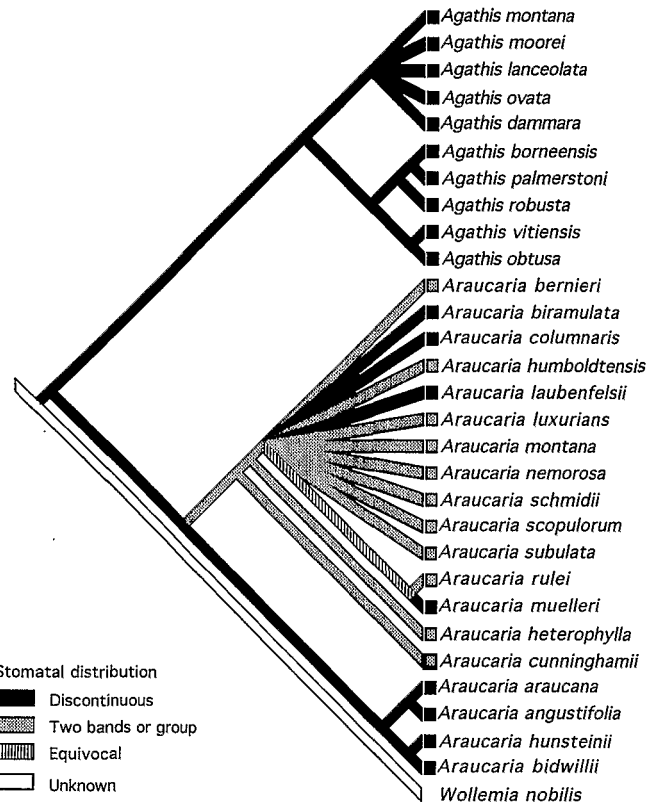


Fig. 5. Parsimonious replacement of stomatal distribution with ACCTRAN and DELTRAN optimization on the most parsimonious phylogenetic tree based on the *rbcL* gene sequences (Fig. 1). There is no difference in the character distribution between ACCTRAN and DELTRAN optimization.

hemispheres, should be separately treated from the extant *Bunya* species. Hypogeal germination can be evaluated as an autapomorphy for *A. bidwillii* in the section. We should add further molecular data to enhance the statistical probability concerning the present position of *A. bidwillii* in the phylogenetic tree.

Evolution of *Araucaria*—The *rbcL* tree indicates that the genus *Araucaria* is divided into two clades. In the cluster of Sections *Araucaria*, *Bunya*, and *Intermedia*, extant species attributed to these sections are distributed in South America, Australia, or New Guinea. This distribution pattern linking South America and Australasia is often considered to be the result of the Mesozoic break up of Gondwanaland followed by continental drift (see Raven and Axelrod, 1972, 1974). Fossils of Sections *Araucaria* and *Intermedia* have also been found only from the Southern Hemisphere (Argentina + Australia and New Zealand, respectively; see Table 1), and fossils assigned to Section *Bunya* should be separately treated from the extant *Bunya* species as discussed above. Therefore, common ancestral taxa of Sections *Araucaria* and *Intermedia*, and possibly Section *Bunya*, were distributed in Gondwanaland during the Mesozoic and the early Tertiary, and their evolution into Sections *Araucaria* and *Intermedia* (and possibly Section *Bunya*) were completed before South America separated from Antarctica, during the Eocene at the latest. The oldest fossil records in these

sections are late Cretaceous (Bose, 1975) and agree well with the fact that there was a continuous landmass from South America to Antarctica, Australia, New Zealand, and New Guinea 70–80 million years ago, in the late Cretaceous (Wilford and Brown, 1994). Therefore, the present finding indicating the monophyly of Sections *Araucaria*, *Intermedia*, and *Bunya* agrees with these fossil and geological facts.

The monophyly of Section *Eutacta* was strongly supported. Section *Eutacta* has been regarded as the oldest taxon together with Section *Bunya* based on their Jurassic to Cretaceous fossil records. In the present study, *rbcL* phylogeny suggests that Section *Eutacta* is older than the other sections. However, recent paleobotanical findings have indicated that some Mesozoic Northern Hemisphere species may have been inappropriately assigned to Section *Eutacta*.

Fossils of *Araucaria* are usually fragmentary, i.e., found as a part of the whole plant and have been discussed in their sectional attributes on the basis of partial fossils such as cones or leaves. Ohsawa, Nishida, and Nishida (1995) found a new specimen of *Araucaria* whose cone was attached to the vegetative organs that had been described as *Yezonia vulgaris*. They reconstructed the whole plant and proposed a new section, *Yezonia*, based on the combination of features quite different from other extant sections. The cone anatomy of this fossil coincided with that of *Araucaria nihongi* (Stockey, Nishida, and Nishida, 1992), which has cones externally similar to those of Section *Eutacta*. External and anatomical features of shoots of *Yezonia* closely resemble *Brachyphyllum*, which is sometimes associated with araucarian cone fossils assigned to Section *Eutacta*. Thus, the taxonomic positions of Mesozoic araucarian fossils that have been included in Section *Eutacta* are now doubtful after the finding of *Yezonia*. Reexamination of Mesozoic fossils assigned to Section *Eutacta* is needed.

Evolution of *Agathis*—Fossils of *Agathis* have been excavated from Tertiary sediments restricted to Australia and New Zealand (Cookson and Duigan, 1951; Florin, 1963; Hill and Bigwood, 1987). The oldest known fossil is a collection of leaves from the middle Cretaceous (Albian) in Australia (Cantrill, 1992), but no cones are known from the Mesozoic. Stockey (1994) stated that *Agathis* is known from the Cretaceous, and Hill (1995) gave its time of appearance as the beginning of the Tertiary. Despite the molecular evidence for the sister-group relationship between *Agathis* and *Araucaria*, our current knowledge of the fossil record only traces *Agathis* back to the Cretaceous/Tertiary boundary and suggests that the genus may always have been more restricted to the southern hemisphere.

Infrageneric relationships of *Agathis* were poorly resolved by the data, and the low sequence divergence suggests the recent diversification of extant agathian species. The bootstrap values are very low in each node of the tree, and we will not discuss the evolution of *Agathis* based on the present trees. We are now examining *matK* sequence data for the Araucariaceae in order to derive a better understanding of the evolution of *Agathis* as well as to solve some other problems uncovered in the present study.

New Caledonian species—New Caledonia possesses 13 endemics of *Araucaria* and five of *Agathis*, and their morphological characteristics and preferred habitats are well diversified (see de Laubenfels, 1972; CTFT, 1975; Veillon, 1978, 1980; Jaffré, 1995). Nevertheless, the very high or identical homology of their *rbcL* gene sequences was observed among the species in each genus (Table 3). High morphological diversity with the low sequence divergence, the low restriction site divergence, or low genetic differentiation is usually observed in endemics to the oceanic islands, by means of rapid adaptive radiation and speciation to new niches (e.g., Carr and Kyhos, 1986; Crawford, Stuessy, and Silva, 1987; Ito and Ono, 1990; Ito et al., 1990; Crawford et al., 1992, 1993; Soejima et al., 1994).

New Caledonia, one of the continental islands, originated from a part of Gondwanaland and was separated from the continent between the Triassic and the end of the Jurassic (Raven and Axelrod, 1974; Paris, 1981). However, a large area of New Caledonia is covered with ultramafic soil derived from peridotite, and it is suggested that this area was formed at the end of the Eocene. Most of the species of Araucariaceae are distributed in this soil (12 of the 13 species in *Araucaria* and four of the five species in *Agathis*). Jaffré (1995) suggested that there was differentiation of new species of *Araucaria* in the post-Eocene, after the emplacement of peridotite. His discussion agrees with the findings of very low sequence divergence in the *rbcL* gene among endemics of *Araucaria* and *Agathis*. It is suggested that the adaptive radiation to new edaphic conditions, i.e., ultramafic soils, caused their rapid differentiation after the Eocene.

As a result, although New Caledonia is an old continental island that had been a part of Gondwanaland, the evolutionary trend of the Araucariaceae is rather like that of oceanic islands. Setoguchi et al. (1997) found a similar pattern in New Caledonian *Nothofagus* using an *atpB-rbcL* intergenic spacer sequence. Further case studies will be needed to examine the origin and speciation of Gondwanan floristic elements in New Caledonia.

LITERATURE CITED

- ALBERT, V. A., M. W. CHASE, AND B. D. MISHLER. 1993. Characterstate weighting for cladistic analysis of protein-coding DNA sequences. *Annals of the Missouri Botanical Garden* 80: 752–766.
- BOSE, M. N. 1975. *Araucaria haastii* Ettingshausen from Shag Point, New Zealand. *Palaeobotanist* 22: 76–80.
- BURROWS, G. E., AND R. A. STOCKEY. 1994. The developmental anatomy of cryptogean germination in bunya pine (*Araucaria bidwillii*). *International Journal of Plant Science* 155: 519–537.
- , T. S. BOAG, AND R. A. STOCKEY. 1992. A morphological investigation of the unusual cryptogean germination strategy of bunya pine (*Araucaria bidwillii*) — an Australian rain forest conifer. *International Journal of Plant Science* 153: 503–512.
- CALDER, M. G. 1953. A coniferous petrified forest in Patagonia. *Bulletin of British Museum (Natural History) Geology* 2: 99–137.
- CANTRILL, D. J. 1992. Araucarian foliage from the Lower Cretaceous of southern Victoria, Australia. *International Journal of Plant Science* 153: 622–645.
- CARR, G. D., AND D. W. KYHOS. 1986. Adaptive radiation in the Hawaiian Silversword alliance (Compositae-Madiinae). II. Cytogenetics of artificial and natural hybrids. *Evolution* 40: 959–976.
- CTFT. 1975. Inventaire des ressources forestieres de la Nouvelle Calédonie. Fascicule 2. Centre Technique Forestier Tropical, Noumea.
- CHASE, M. W., et al. 1993. Phylogenetics of seed plants: an analysis of

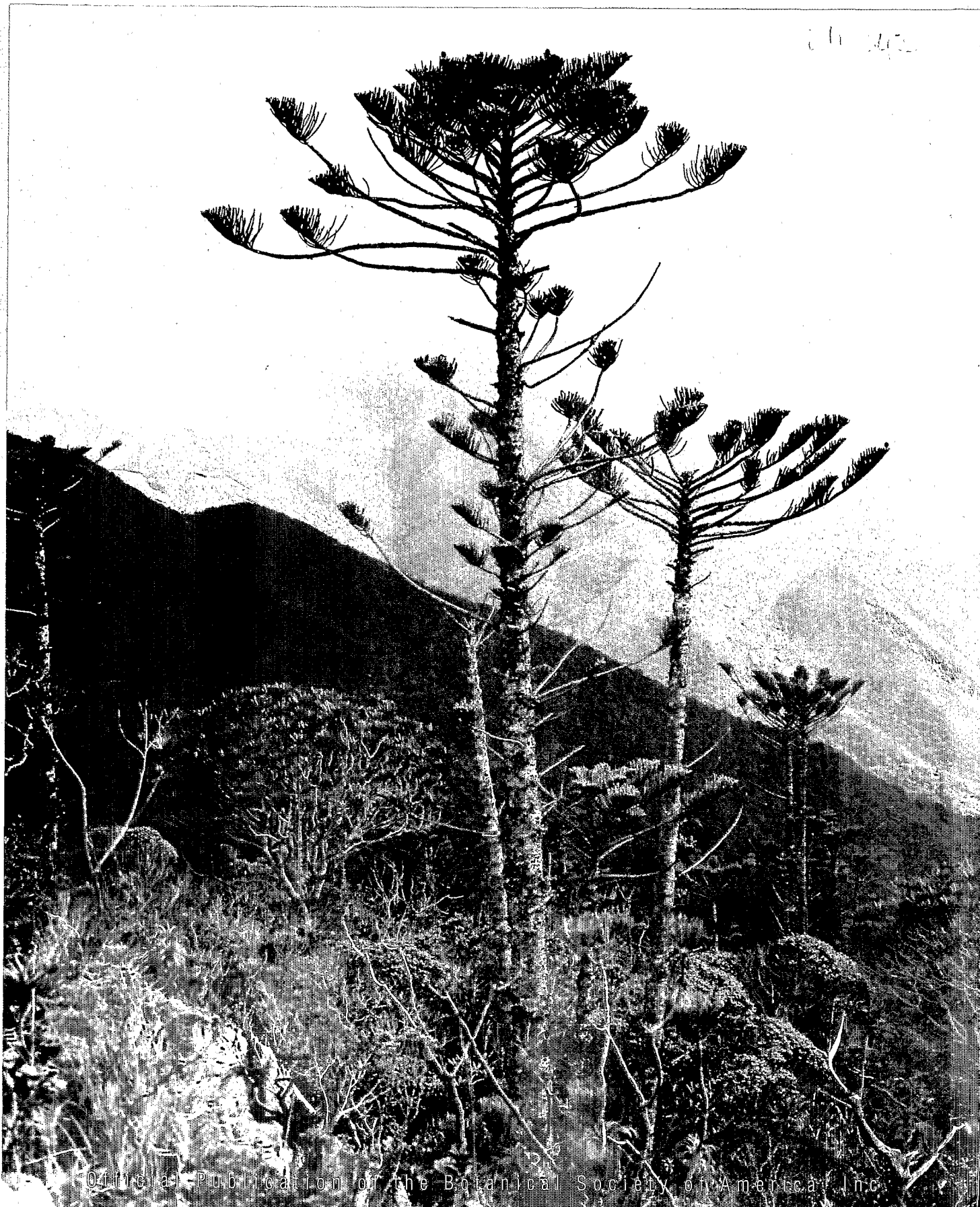
- nucleotide sequences from the plastid gene *rbcL*. *Annals of the Missouri Botanical Garden* 80: 528–580.
- COOKSON, I. C., AND S. L. DUIGAN. 1951. Tertiary Araucariaceae from southeastern Australia, with notes on living species. *Australian Journal of Scientific Research Ser. B*, 4: 415–449.
- CRAWFORD, D. J., T. F. STUESSY, AND O. M. SILVA. 1987. Allozyme divergence and the evolution of *Dendroseris* (Asteraceae: Lactuceae) on the Juan Fernandez Islands. *Systematic Botany* 12: 433–443.
- , M. B. COSNER, M. HAINES, O. M. SILVA, AND M. BAEZA. 1992. Evolution of the genus *Dendroseris* (Asteraceae: Lactuceae) in the Juan Fernandez Islands: evidence from chloroplast and ribosomal DNA. *Systematic Botany* 17: 676–682.
- , ———, ———, ———, AND ———. 1993. Ribosomal and chloroplast DNA restriction site mutations and the radiation of *Robinsonia* (Asteraceae: Senecioneae) on the Juan Fernandez Islands. *Plant Systematics and Evolution* 184: 233–239.
- DE LAUBENFELS, D. J. 1972. Gymnosperms. In A. Aubreville and J. F. Leroy [eds.], *Flore de la Nouvelle-Calédonie et Dependances*. Museum National d'Histoire Naturelle, Paris.
- . 1988. Araucariaceae. *Flora Malesiana Series 10*, 3: 419–442.
- FELSENSTEIN, J. 1985. Confidence limits on phylogenies: an approach using the bootstrap. *Evolution* 39: 783–791.
- , AND H. KISHINO. 1993. Is there something wrong with the Bootstrap on phylogenies? A reply to Hillis and Bull. *Systematic Biology* 42: 193–200.
- FLORIN, R. 1963. The distribution of conifer and taxad genera in time and space. *Acta Horti Bergiana* 20: 122–312.
- HASEBE, M., AND K. IWATSUKI. 1990. *Adiantum capillusveneris* chloroplast DNA clone bank: as useful heterologous probes in the systematics of the leptosporangiate ferns. *American Fern Journal* 80: 20–25.
- , T. OMORI, M. NAKAZAWA, T. SANO, M. KATO, AND K. IWATSUKI. 1994. *rbcL* gene sequences provide evidence for the evolutionary lineages of leptosporangiate ferns. *Proceedings of the National Academy of Sciences, USA* 91: 5730–5734.
- HILL, R. S. 1995. Conifer origin, evolution and diversification in the Southern Hemisphere. In N. J. Enright and R. S. Hill [eds.], *Ecology of the southern conifers*, 10–29. Cambridge University Press, Cambridge.
- , AND A. J. BIGWOOD. 1987. Tertiary gymnosperms from Tasmania: Araucariaceae. *Alcheringa* 11: 325–335.
- ITO, M., AND M. ONO. 1990. Allozyme diversity and the evolution of *Crepidiastrum* (Compositae) on the Bonin Islands. *Botanical Magazine, Tokyo* 103: 449–459.
- , A. SOEJIMA, C. ENDO, AND M. ONO. 1990. Adaptive radiation of the endemic plants in the Bonin Islands: speciation observed with allozyme polymorphism. *Ogasawara Kenkyu Nenpo* 14: 15–20 (in Japanese).
- JAFFRÉ, T. 1995. Distribution and ecology of the conifers of New Caledonia. In N. J. Enright and R. S. Hill [eds.], *Ecology of the southern conifers*, 171–196. Cambridge University Press, Cambridge.
- JONES, W. G., K. D. HILL, AND J. M. ALLEN. 1995. *Wollemia nobilis*, a new living Australian genus and species in the Araucariaceae. *Telopea* 6: 173–176.
- MABBERLEY, D. J. 1987. *Plant-Book—a portable dictionary of the higher plants*. Cambridge University Press, Cambridge.
- MACPHAIL, M. K. 1997. Comment on M. Pole (1994): 'entirely long distance dispersal?' *Journal of Biogeography* 24: 113–117.
- MADDISON, W. P., AND D. R. MADDISON. 1992. *MacClade: analysis of phylogeny and character evolution*, ver. 3.0. Sinauer, Sunderland, MA.
- MILLER, C. N. 1977. Mesozoic conifers. *Botanical Review* 43: 217–280.
- . 1988. The origin of modern conifer families. In C. B. Beck [ed.], *Origin and evolution of gymnosperms*, 448–486. Columbia University Press, New York, NY.
- OHSAWA, T., H. NISHIDA, AND M. NISHIDA. 1995. *Yezonia*, a new section of *Araucaria* (Araucariaceae) based on permineralized vegetative and reproductive organs of *A. vulgaris* comb. nov. from the upper Cretaceous of Hokkaido, Japan. *Journal of Plant Research* 108: 25–39.
- PARIS, J. P. 1981. *Geologie de la Nouvelle Calédonie, un essai de synthèse*. Bureau de Recherches Géologiques et Minières, Orleans, France.
- POLE, M. S. 1994. The New Zealand flora - entirely long distance dispersal? *Journal of Biogeography* 21: 625–635.
- RAVEN, P. H., AND D. I. AXELROD. 1972. Plate tectonics and Australasian palaeobiogeography. *Science* 176: 1379–1386.
- , AND ———. 1974. Angiosperm biogeography and past continental movements. *Annals of the Missouri Botanical Garden* 61: 539–673.
- SETOGUCHI, H., AND H. OHBA. 1995. Phylogenetic relationships in *Crossostylis* (Rhizophoraceae) inferred from restriction site variation of chloroplast DNA. *Journal of Plant Research* 108: 87–92.
- , M. ONO, H. DOI, AND M. TSUDA. 1997. Phylogeny and biogeography of *Nothofagus* based on the sequences of *atpB-rbcL* intergenic spacer. *Journal of Plant Research* 110: 469–482.
- SMITH, A. C. 1981. *Flora Vitiensis Nova*, vol. 2. Pacific Tropical Botanical Garden, Hawaii, HI.
- SOEJIMA, A., H. NAGAMASU, M. ITO, AND M. ONO. 1994. Allozyme diversity and evolution of *Symplocos* (Symplocaceae) on the Bonin (Ogasawara) Islands. *Journal of Plant Research* 107: 221–227.
- STOCKEY, R. A. 1975. Seeds and embryos of *Araucaria mirabilis*. *American Journal of Botany* 62: 856–868.
- . 1978. Reproductive biology of Cerro Cuadrado fossil conifers: Ontogeny and reproductive strategies in *Araucaria mirabilis* (Spaggiolini) Windhausen. *Palaeontographica B* 166: 1–15.
- . 1980a. Anatomy and morphology of *Araucaria sphaerocarpa* Carruthers from the Jurassic inferior Oolite of Bruton, Somerset. *Botanical Gazette* 141: 116–124.
- . 1980b. Jurassic araucarian cone from southern England. *Palaeontology* 23: 657–666.
- . 1982. The Araucariaceae: an evolutionary perspective. *Review of Palaeobotany and Palynology* 37: 133–154.
- . 1994. Mesozoic Araucariaceae: morphology and systematic relationships. *Journal of Plant Research* 107: 493–502.
- , AND I. ATKINSON. 1993. Cuticle micromorphology of *Agathis* Salsbury. *International Journal of Plant Science* 154: 187–225.
- , AND H. KO. 1986. Cuticle micromorphology of *Araucaria* de Jussieu. *Botanical Gazette* 147: 508–548.
- , M. NISHIDA, AND H. NISHIDA. 1990. Structure and diversity of the woody conifer seedling-like structures from the upper Cretaceous of Hokkaido, Japan. *Botanical Gazette* 151: 252–262.
- , ———, AND ———. 1992. Upper Cretaceous araucarian cones from Hokkaido: *Araucaria nihongii* sp. nov. *Review of Palaeobotany and Palynology* 72: 27–40.
- , ———, AND ———. 1994. Upper Cretaceous araucarian cones from Hokkaido and Saghalien: *Araucaria nipponensis* sp. nov. *International Journal of Plant Science* 155: 800–809.
- SWOFFORD, D. L. 1993. PAUP: phylogenetic analysis using parsimony. Mac ver. 3.1.1 (Computer program and manual). Illinois Natural History Survey, Champaign, IL.
- VEILLON, J.-M. 1978. Architecture of the New Caledonian species of *Araucaria*. In P. B. Tomlinson and M. H. Zimmermann [eds.], *Tropical trees as living systems*, 233–245. Cambridge University Press, Cambridge.
- . 1980. Architecture des especes neo-calédoniennes du genre *Araucaria*. *Candollea* 35: 609–640.
- WHITMORE, T. C. 1977. A first look at *Agathis*. Oxford University Tropical Forestry Papers Number 11. Department of Forestry, University of Oxford, Oxford.
- . 1980. A monograph on *Agathis*. *Plant Systematics and Evolution* 135: 41–69.
- WIELAND, G. W. 1935. The Cerro Cuadrado Petrified Forest. *Carnegie Institute of Washington Publication* 449: 1–183.
- WILDE, M. H., AND A. J. EAMES. 1952. The ovule and 'ed' of *Araucaria bidwillii* with discussion of the taxonomy of the genus. II. Taxonomy. *Annals of Botany New Series* 16: 27–47.
- WILFORD, G. E., AND P. J. BROWN. 1994. Maps of late Mesozoic-Cenozoic Gondwana break-up: Some paleogeographical implications. In R. S. Hill [ed.], *History of the Australian vegetation: Cretaceous to recent*, 5–13. Cambridge University Press, Cambridge.

B O T A N Y

N O V E M B E R 1 9 9 8

V O L U M E 8 5

N U M B E R 1 1



Handwritten text at the bottom of the page, possibly a signature or date.