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10. PALYNOLOGY OF SITES 815 AND 823: THE NEOGENE VEGETATION HISTORY OF COASTAL NORTHEASTERN AUSTRALIA[1]

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ABSTRACT

Few palynological studies have been conducted in northeastern Australia, and Sites 815 and 823 add substantially to the record. The vegetation during the Neogene sequence was lowland rainforests with common araucarians and Casuarinaceous sclerophyllous forests. Myrtaceae was scarce, unlike in the rest of Australia, where it was common throughout the Neogene. Surprisingly, little change occurred during the Neogene. The expectation that the fragmentary, undated deposits on land could be correlated with these well-dated sites has not been realized. Each Neogene study reveals substantial locality differences, commensurate with geographic variation seen in the vegetation today.

INTRODUCTION

Sites 815 and 823 are located off the northeastern coast of Australia, just seaward of the Great Barrier Reef (Fig. 1). Site 815 was drilled in 450 m of water on the northern margin of the Marion Plateau, 250 km east of the Australian mainland (Fig. 1). The site contains a Pleistocene to middle Miocene succession of nannofossil and foraminiferal oozes, which are the basis of a good age control. Site 823 was drilled in 1638 m of water in the central-western Queensland Trough and contains a similar succession but with some calcareous turbidities. The lithologies are similar at both sites and are discussed in detail elsewhere in this volume.

Northeastern Queensland is of special phytogeographic interest because it has many plant taxa not found elsewhere in Australia (Burbidge, 1960). This region has the highest rainfall and the greatest area of rainforest in Australia. These unique rainforests have world heritage listing, yet little is known of their history. Previous reports on the Tertiary period of Queensland are as follows: Hekel (1972) recorded early Tertiary–Pliocene assemblages from central and southern coastal Queensland. The dating and recognition of units within his Paleogene sequence is disputed (Foster, 1982), but the Neogene sequence is accepted. Foster (1982) documented middle late Eocene palynofloras of the Yaamba Basin. The floras are diverse and have many taxa in common with southeastern Australia. Dudgeon (1983) described a suite of probable proteaceous pollen from the Eocene of the Yaamba Basin. Wood (1986) reported on late Oligocene–early Miocene assemblages from Fraser Island in southern Queensland. The diverse floras share many taxa with southeastern Australia. Kershaw and Sluiter (1982) recorded late Tertiary or early Pleistocene pollen spectra from Butcher's Creek on the Atherton Tablelands. All of these studies give glimpses of the Tertiary vegetation. However, they are too fragmentary for a coherent history, with the exception of Hekel's (1972) Neogene section, which is compared with these sites later. The relatively complete Neogene sequences from Sites 815 and 823 should contribute significantly to the vegetation history of northern Australia, particularly during a time when the vegetation is thought to have been changing rapidly.

MATERIALS AND METHODS

Thirty-eight samples from Site 815 and 47 from Site 823 were collected for this study by Leg 133 shipboard scientists. The samples were processed at the Palynological Laboratory of the New South Wales Geological Survey. Samples were first desegregated in 30% HCl

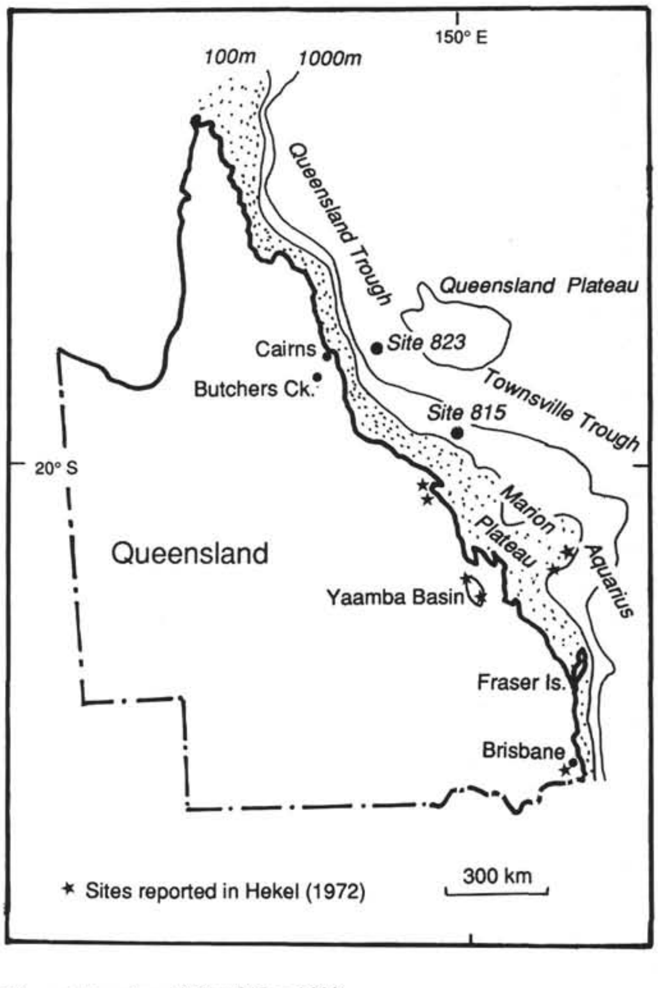

Figure 1. Location of Sites 815 and 823.

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and left overnight in 30% HF. After repeated washings in distilled water, they were sieved on an 8 mm screen with the aid of an ultrasonic needle. The residue was then further concentrated by the use of the heavy liquid solution $ZnBr_2$ S.G. 2.1 specific gravity. Residues were mounted in Eukitt and stored in the Palaeoecology Collection of the Institute of Antarctic and Southern Ocean Studies at the University of Tasmania, Hobart. Age control is based on nannofossil and foraminifer data presented in Davies, McKenzie, Palmer-Julson, et al. (1991).

POLLEN IN MARINE SEDIMENTS

Marine sediments contain a record of the regional vegetation and climate that may be considered better than most continental deposits (Heusser, 1986/87). In a review of research on deep-sea cores in the northeastern Atlantic Ocean, northwest Pacific Ocean, and Arabian Sea, Heusser (1986/87) demonstrated that, over the last 140,000 yr, climatic records derived from the pollen of land-based vegetation are in agreement with those derived from marine microfossils (foraminifers and radiolarians) and with ice-sheet volume (derived from oxygen isotopes). Subsequent studies (e.g., Rossignol-Strick and Planchair, 1989; Heusser, 1990) are in accord with these earlier reports.

Interpretation of pollen in marine sediments relies on surveys of the distribution of pollen in seafloor surface sediments and their relationship to the terrestrial vegetation. Heusser (1988) concluded that most studies show a systematic distribution of pollen in marine sediments that is related to environmental and sedimentological factors. These factors include the composition of the vegetation, pollen production, dispersal, and eolian, fluvial, and marine transport. In a study of the distribution of pollen on the continental margin off northern California, Heusser (1988) demonstrated that pollen rapidly increases seaward on the shelf and is present in relatively large quantities in water depths of greater than 50 m. She also found tongues of high pollen concentration projecting from river mouths toward a submarine canyon. Sediment traps on the mid-slope recorded seasonal changes in pollen abundance, and a similar trend also was found in sediment traps in the rivers. Pollen deposition on the slope was strongly influenced by the physical processes involved in the sedimentation of fine-grained, terrigenous particles, demonstrating that in this region, fluvial rather than eolian processes are the major means of transporting pollen from land onto the shelf (Heusser, 1978). Most important, Heusser (1988) was able to show that pollen deposited on the California continental margin was derived from contemporary vegetation and clearly reflected the major vegetation formations onshore.

THE POLLEN RECORD

The pollen types recorded, their botanical affinities, and habitat preference are listed in Tables 1 and 2. The affinities of a previously undocumented fossil spore type with some species of *Pteris* are established in the appendix. Time did not permit a full documentation of all spore and pollen taxa. Relative abundance and ranges are shown in Figures 2 and 3.

Araucariaceae pollen is the most abundant type at both sites. Frequencies decrease in the upper part of Site 815, and there may be a cyclical variation at Site 823. *Podocarpus* spp. pollen is moderately abundant, with slightly more at Site 823 than at Site 815. The highest frequencies are present in the upper Miocene of Site 815. Pollen of *Dacrydium* spp., *Dacrycarpus,* and, rarely, *Phyllocladus* and *Microcachrys* are present also (Figs. 2 and 3).

Pollen of the rainforest angiosperms registers in low frequencies and the occurrence of most is scattered. *Nothofagus* pollen is consistently present only at the base of Site 823 in low frequencies. Gyrostemonaceae pollen is usually present in the upper part of Site 815. Pollen of rainforest Myrtaceae is rare.

Pollen of mangroves has a very low representation, though slightly more at Site 823.

Moderate pollen frequencies of Casuarinaceae are recorded at both sites, with a tendency to cyclic variation at Site 823. Where Araucariaceae is high, Casuarinaceae is usually low and vice versa, but this is not always the case.

Pollen of other sclerophyllous taxa registers in low frequencies. Importantly, *Eucalyptus* spp. and other Myrtaceae are low and sporadic, with the best representation at the top of Site 815. Pollen of *Acacia* and *Dodonaea* is better represented at Site 815.

Pollen of herbaceous taxa is moderate at Site 815, and Cyperaceae and Asteraceae increase up the section. Frequencies are much lower at Site 823 (Figs. 2 and 3).

Spores are diverse and moderately abundant. Cyathea is the most common type. Other types usually present are shown in Figures 2 and 3.

Some of the taxa represented in the pollen record no longer grow in northeastern Queensland. *Dacrydium* and *Dacrycarpus* are found in New Guinea, New Caledonia, and New Zealand. *Phyllocladus* occurs in New Guinea, New Zealand, and Tasmania, whereas *Microcachrys* is a Tasmanian endemic. The *menzeisii* type of *Nothofagus* is found in southeastern Queensland and the coastal strip to the south, but the *brassii* type is restricted to New Guinea and New Caledonia. *Dodonaea triquetra* has a distribution similar to that of the *menzeisii* type of *Nothofagus.* The mangrove *Brownlowia* occurs in the Solomon Islands and Malaysia. *Eucalyptus spathulata* is endemic to southeastern Western Australia, but it had a southern coastal distribution in the Pliocene (Martin and Gadek, 1988). Indeed, all these taxa and many others listed in Tables 1 and 2 had a much wider distribution during the Tertiary.

Pollen Representation

Wind-pollinated plants usually produce copious pollen and may be overrepresented in pollen spectra. On the other hand, insect- or animal-pollinated plants produce meager quantities of pollen and such taxa usually are underrepresented. In this study, all of the gymnosperms, *Nothofagus, Celtis/Trema*, Casuarinaceae, Poaceae, Cyperaceae and Restionaceae are wind-pollinated. All other angiosperms are pollinated by insects or other animals, hence they are usually only found in low frequencies. Myrtaceous taxa are not wind-pollinated, but experience has shown that they may form large portions of the pollen spectra. These factors are taken into account in the interpretation of the pollen spectra. Surveys of pollen spectra beneath different vegetation types (e.g., Sluiter and Kershaw, 1982) and pollen trapping (Kershaw and Hyland, 1975) also assist interpretation.

Habitat Classification

The taxa identified in the cores are classified according to habitat preference (Table 1). Habitat classification may be problematic because of the level of identification of the pollen type. For example, pollen of Casuarinacea may be either the rainforest *Gymnostoma* or the sclerophyllous *Casuarina/Allocasuarina*. These taxa are not distinguishable as to pollen types (Kershaw, 1970). Today, sclerophyllous taxa are widespread in the Australian vegetation, whereas *Gymnostoma* has a very restricted distribution, and for this reason, Casuarinaceae pollen is here given a sclerophyllous classification. Gyrostemonaceae is best known in arid regions, but one rainforest species is known (Williams, 1979), hence the rainforest classification. The separation of Myrtaceae pollen types in sclerophyllous and rainforest taxa is at best an approximation, as identification of the pollen with extant taxa is extremely difficult.

Species of Proteaceae are found in both rainforests and sclerophyllous vegetation. Pollen types identifiable only to the family level have been put in the sclerophyll category. Proteaceous pollen is rare, hence any error incurred is small.

THE VEGETATION

There was a considerable rainforest element, and araucarian forests were dominant. *Podocarpus* and other gymnosperms were present. Rainforest angiosperms were important also, in spite of underrepre-

Table 1. Pollen types.

Fossil name	Reference	Habitat	Botanical affinity
Gymnosperms:			
Araucariacites australis	1	R	*Araucariaceae*
Dacrycarpites australiensis	1	R	*Dacrycarpus*
Dilwynites granulatus	7		(?)Araucariaceae
Lygistepollenites florinii	7, 13	R	*Dacrydium (Podocarpaceae)*
Microcachryidites antarcticus	14	(?)R	*Microcachrys (Podocarpaceae)*
Phyllocladidites palaeogenicus	14	R	*Phyllocladus (Podocarpaceae)*
Podocarpidites spp.		R,S	*Podocarpus* spp. *(Podocarpaceae)*
Trisaccites micropteris	14	R	(?)*Phyllocladus (Podocarpaceae)*
Casuarinaceae:			
Haloragacidites harrisii	7, 15	S,R	*Gymostoma, Casuarina/ Allocasuarina*
Casuarinidites cainozoicus	15, 16		
Myrtaceae:			
Myrtaceidites eucalyptoides	15	S	Angophora/bloodwood eucalypt type
Myrtaceidites cf. *M. eucalyptoides*		S	Other eucalypts
Myrtaceidites cf. *Eucalyptus spathulata*	17	S	*E. spathulata*
M. mesonesus	15		(?)*Eucalyptus* (?)*Meterosideros*
M. parvus	15	R	*Baeckea/Backhousia/Tristania*
M. verrucosus	7	R	*Rhodamnia/Archirhodomyrtus,* etc.
Myrtaceae indet.			
Nothofagus:			
Nothofagidites asperus	3, 13	R	*Nothofagus, menzeisii* type
N. emarcidus	7, 18	R	*Nothofagus, brassii* type
N. falcatus	7, 18	R	*Nothofagus, brassii* type
N. longispinosus	18	R	*Nothofagus, brassii* type
Low-frequency angiosperms:			
Cyperaceaepollis spp.	5	H	Cyperaceae
Graminidites monoporites	1	H	Poaceae
Tubulifloridites pleistocenicus	1	H	Asteraceae
Tubulifloridites spp.	1, 7	H	Asteraceae
Chenopodipollis chenopodiaceoides	1, 5	H	Chenopodiaceae/Amaranthaceae
Acacia myriosporites	1	S	*Acacia (Mimosaceae)*
'Ephedra' notensis	1	R	(?)Araceae
Avicennia	2	M	*Avicennia (Verbenaceae)*
(?)*Brownlowia* type	2	M	(?)*Brownlowia (Tiliaceae)*
Canthiumidites sp.	3	R	*Canthium* (Rubiaceae)
Cupaneidites orthoteichus	4	R	*Cupanieae (Sapindaceae)*
Dodonaea sphaerica	1	S	*Dodonaea* spp. *(Sapindaceae)*
Ericipites sp.	1	S	*Ericales*
Florschuetzia sp.	9	M	*Sonneratia (Sonneratiaceae)*
Guerttardidites sp.	3	R	*Guerttardia* (Rubiaceae)
Gyrostemonaceae	5	R	Gyrostemanaceae
cf. *Hakea*		S	*Hakea* (Proteaceae)
Haloragacidites haloragoides	4	S	*Haloragis* (Haloragaceae)
H. myriophylloides	4	W	*Myriophyllum* sp. (Haloragaceae)
Loranthaceae	6		*Loranthaceae*
Malvacearumpollis sp.	5	(?)R	Malvaceae
Malvacipollis sp.	7, 8	R	Austrobuxus/Dissiliaria (Euphorbiaceae)
Micrantheum sp.	1	S	*Micrantheum* (Euphorbiaceae)
Milfordia homeopunctata	7	S	Restionaceae
M. hypolaeoides	1	S	Restionaceae
Milfordia sp.		S	Restionaceae
cf. Moraceae	10		Moraceae
Myoporaceae			Myoporaceae
cf. *Nuxopollenites* sp.	5	S	*Dodonaea triquetra (Sapindaceae)*
Proteacidites cf. *P. pachypolus*	7		Proteaceae
Proteacidites cf. *P. truncatus*	1		Proteaceae
Proteacidites sp.			Proteaceae
Psilatricolporites operculatus	9, 8	R	*Coelebogyne* (Euphorbiaceae)
Rostriapollenites robusta	11	M	*Barringtonia (Barringtoniaceae)*
cf. Sapotaceae		R	Sapotaceae
Sparganiacepollenites barungensis	1	W	Sparganiaceae
S. sphericus	12	W	Sparganiaceae
Spinozonocolpites sp.	7, 9	M	*Nypa* (Arecaceae)
Stephanocolpites oblatus	1		Unknown
Tasmannia (Drimys) tetradites	1	R	*Tasmannia (Winteraceae)*
(?)Thymeleaceae		S	Thymeleaceae
Tricolporites endobalteus	8	R	*Macaranga/Mallotus* (Euphorbiaceae)
T. substriatus	1	R	(?)Anacardiaceae
Triporopollenites bellus	6, 7	R	*Gardenia ('Randia')* cf. *G. chartaceae* (Rubiaceae)
T. ulmiformis	3	R	cf. *Trema/Celtis (Ulmaceae)*
Zonocostites ramonae	9	M	Rhizophoraceae
Unknown monosulcates		(?)R	(?)Arecaceae

Notes: Type of habitat: M = mangrove, R = rainforest, S = sclerophyll, W = swamp/water, H = herbaceous. Where two types are given, the major type is listed first and the minor type is second. Reference where the species may be found: 1 = Martin (1973b), 2 = Muller (1964), 3 = Khan (1976), 4 = Cookson and Pike (1954b), 5 = Truswell et al. (1985), 6 = Martin (1978), 7 = Stover and Partridge (1973), 8 = Martin (1974), 9 = Germeraad et al. (1968), 10 = Luly et al. (1980), 11 = Playford (1982), 12 = Mildenhall and Crosbie (1979), 13 = Cookson and Pike (1953), 14 = Cookson and Pike (1954a), 15 = Cookson and Pike (1954b), 16 = Kershaw (1970), 17 = Martin and Gadek (1988), 18 = Dettmann et al. (1990).

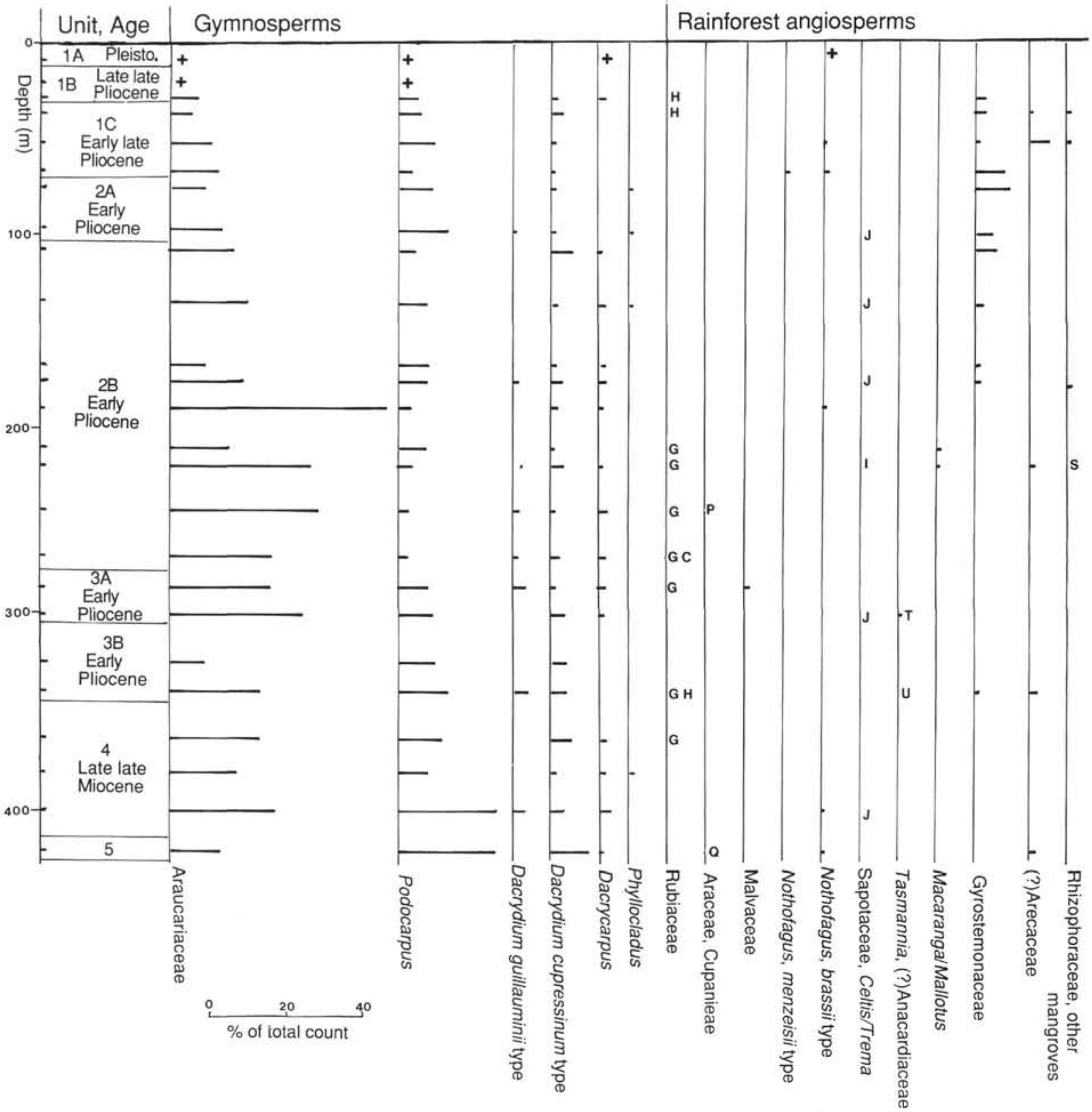

Figure 2. Pollen diagram of Site 815 core. A = *Avicennia;* B = *Barringtonia;* C = *Canthium;* D = (?)*Brownlowia;* E = *Austrobuxux/Dissiliaria;* F = *Coelebogyne;* G = *Guerttardia;* H = *Gardenia ("Randia") chartaceae;* I = Sapotaceae; Ia = *Cingulatisporites bifurcatus;* J = cf. *Trema/Celtis;* L = Ericales; M = *Microcachrys;* N = *Nypa;* O = Myoporaceae; P = (?)Araceae; Pu = *Stenochlaena palustris;* Pr = *Polypodiaceoisporites retirugatus;* Q = Cupanieae; Rc = *Reticulatisporites cowrensis;* S = *Sonneratia;* Sa = *Schizaea* cf. *S. asperula;* Sp = *Schizaea* cf. *S. papuana;* Sq = *Schizaea* cf. *S. punctata;* T = *Tasmannia;* U = (?)Anacardiaceae; V = *Eucalyptus spathulata;* Z = *Dodonaea triquetra;* + = rare, not counted.

sentation in the pollen diagram. *Nothofagus* was absent or very rare, at least in the coastal vegetation. Rainforest Myrtaceae were rare, which is surprising, as they are important in modern rainforests.

Sclerophyllous forests were considerable, but Casuarinaceae was dominant, not *Eucalyptus*. No doubt there was a mosaic between the two major types of vegetation: the rainforests occupying the better soils and wetter sites, and the sclerophyllous communities on the poorer soils and drier sites, as is seen today. Some cyclical expansion/contraction existed between the two types, but it was relatively minor.

Mangrove taxa were limited, given the rich mangrove flora of northern Australia today (Lear and Turner, 1977). Unusually little mangrove pollen was found, considering the location of these cores. Mangroves form distinctive communities along sheltered shorelines and estuaries. It may be that suitable habitats were relatively minor (see Kershaw, McKenzie, and McMinn, this volume). Moreover, most mangroves are pollinated by insects or other animals, and hence underrepresented. Not all the species in the botanical taxon identified with the pollen type are mangroves; Rhizophoraceae, in particular, contains nonmangroves.

The herbaceous element was relatively minor, although it increased toward the top of the sequence, especially at Site 815. Cyperaceae was the most abundant, suggesting that swamps became more common during the Pliocene. The increase, however, was small.

When the two sites are compared, they are generally similar, but with slightly more sclerophyll (see *Acacia* and *Dodonaea* in Fig. 2) and more swamp vegetation at Site 815, but these differences are

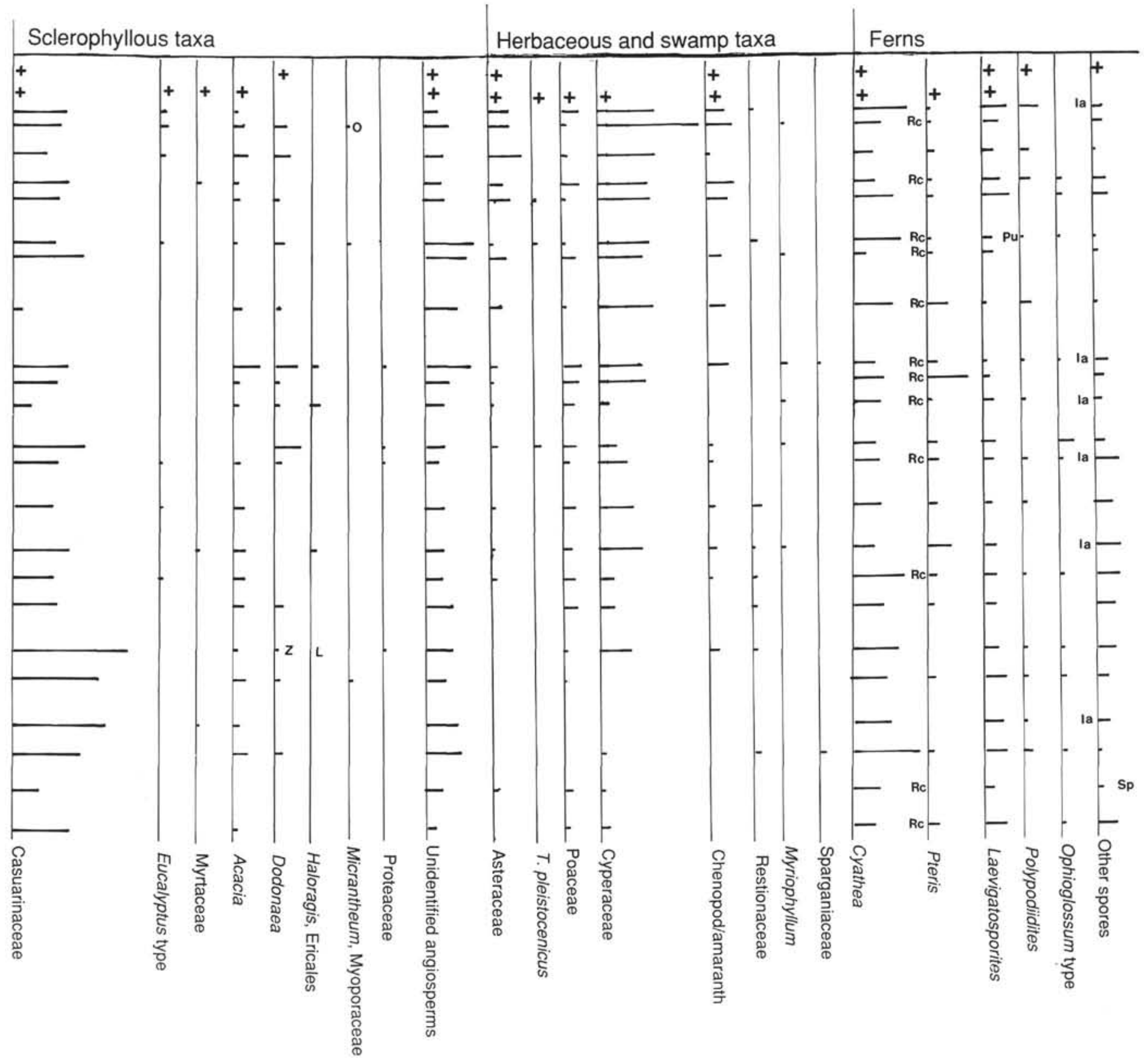

Figure 2 (continued).

relatively minor. Site 823 would have had proportionately more rainforest than Site 815.

These sites may be compared with the Neogene sequence reported by Hekel (1972), from an offshore well, A.O.G. Aquarius-1, near the southern end of the Marion Plateau (Fig. 1). Araucarians are relatively common throughout the section. The other gymnosperms (bisaccates in Fig. 4) are well represented, but Hekel does not give quantitative data on the individual pollen type. *Nothofagus* is common in the lower Miocene sequence, but it predates the sequences from Sites 815 and 823. *Nothofagus* is not recorded from the comparable upper Miocene–Pliocene part of the Aquarius-1 well site. There is appreciable Myrtaceae, increasing in the upper Miocene–Pliocene. Hekel does not separate rainforest and sclerophyllous Myrtaceae in his pollen diagram, but both are present. Casuarinaceae is moderate. The herbaceous element is small, and there are minor amounts of mangrove pollen (Fig. 4).

When the Aquarius-1 well site is compared with these sites, the major difference is the plentiful myrtaceous content at Aquarius-1 and its rarity at Sites 815 and 823.

PALYNOSTRATIGRAPHY

A major problem for palynostratigraphy of Australian deposits is their fragmentary nature. The well-dated reference section most often used for correlation is for the Gippsland Basin (Stover and Partridge, 1973) in the most southeasterly part of Australia. The correlation of palynofloras with the zonation for the Gippsland Basin becomes less certain with distance, and some taxa are known to have different ranges elsewhere. Moreover, the quantitative relationships may be very different (Martin, 1987; Macphail and Truswell, 1989). These discrepancies are to be expected: the vegetation is not uniform and may vary considerably with the geographic region. These well-dated,

Table 2. Spore types.

Fossil name	Reference	Botanical Affinity
cf. *Asplenium*		(?)*Asplenium*
Baculatisporites scabridis	2	(?)Anthocerotae or a fern?
Baculatisporites sp.		
Cingulatisporites bifurcatus	1	Anthocerotae
Cingulatisporites cf. *C. ornatus*	1	(?)Pteridaceae
Crassoretitriletes vanraadshooveni	4	cf. *Lygodium microphyllum*
Cyathea paleospora	1	*Cyathea*
Cyathidites australis		*Cyatheaceae*
C. subtilis	3, 1	*Cyathea*
Deltoidospora inconspicua	1	(?)Adiantaceae
Dictyopyllidites sp. A	2	(?)Gleicheniaceae
Foveotriletes lacunosus	3	
Foveotriletes sp.	2	cf. *Lycopodium phelgmana*
Ophioglossumsporites novaguineensis	6	*Ophioglossum*
Gleicheniidites circinidites	1	*Gleichenia*
Hypolepis sp.	1	*Hypolepis*
Laevigatosporites ovatus	1	
Latrobosporites sp.		
Lycopodium sp.		*Lycopodium*
Matonisporites cf. *M. ornamentalis*	3	
Microfoveolatosporis spp.	2	Schizaceae
Peromonoletes sp.		
Polypodiaceoisporites retirugatus	2	Pteris type
Polypodiidites sp.		
Polypodiisporites usmensis	2	*Stenochlaena palustris*
Pteris type	4	*Pteris*
Reticulatisporites cowrensis	1	
R. echinatus	1	
Reticuloidosporites minispora	1	
Rouseisporites sp.	1	(?)Hepatic
Rugulatisporites mallatus	3	
R. trophus	3	cf. *Lycopodium clavatum* (2)
Selaginella sp.		*Selaginella*
Schizaea cf. *S. asperula*	7	*Schizaea*
Schizaea cf. *S. papuana*	7	*Schizaea*
Schizaea cf. *S. punctata*	7	*Schizaea*
Small verrucate trilete		
Todisporites sp.	1	(?)Osmundaceae
Verrucosisporites cristatus		

Note: Reference where the species may be found: 1 = Martin (1973b), 2 = Playford (1982), 3 = Stover and Partridge (1973), 4 = See Appendix, 5 = Germeraad et al. (1968), 6 = Khan (1976), 7 = Cookson (1956).

deep-sea sites, located in a poorly known region of Australia, offered hope that they might be used for dating the fragmentary deposits on the land in a region where correlation with the Gippsland Basin sequence is inappropriate. Unfortunately, these expectations will not be met, for the following reasons.

The two sites of this study and the Aquarius-1 well site show a locality difference commensurate with that seen today between these regions (discussed further later). Experience with the Neogene in southeastern Australia shows that palynology mainly reflects locality differences. This is also commensurate with present-day differences, and attempts at the classic methods of palynostratigraphy meet with limited success. Ranges of diagnostic species do not work, mainly because most of the taxa range throughout the Neogene, in one geographic province or another. Moreover, most of the taxa are living today in some other region not too distant. Quantitative differences may be used locally, but extrapolation further afield requires extreme caution. For example, the *brassii* type of *Nothofagus* disappeared from the pollen record of the western slopes of New South Wales in the middle late Miocene (Martin, 1987), but it has been found in the late Pliocene–Pleistocene of Lake George in the Highlands (McEwen Mason, 1989), some 300 km away. This difference is not surprising, as the *brassii* type of *Nothofagus* requires a humid climate and cannot tolerate dryness. Lake George in the Highlands has a much wetter climate than that of the western slopes, hence *Nothofagus* was able to exist much longer in the face of developing aridity than in the inland regions.

Butcher's Creek on the Atherton Tablelands (Fig. 1) is thought to be Pliocene–Pleistocene in age (Kershaw and Sluiter, 1982). The deposits are capped by basalts too weathered to be dated but coming from a volcanic province with a range of ages from 0.8 to 3 m.y. The palynofloras have abundant *Nothofagus* of the *brassii* type, and *Podocarpus* is the most common gymnosperm. Araucariaceae is rare. Overall, Casuarinaceae is the most common pollen type. There are some sclerophyllous types and a wealth of rainforest angiosperm pollen types, and, although *Eucalyptus* is not specified, there is appreciable Myrtaceae pollen. The herbaceous element is minor: the vegetation was mainly forests.

The Butcher's Creek pollen spectra contrast with those from the surface samples in the area in that Myrtaceae and Casuarinaceae dominate the palynofloras. The *brassii* type of *Nothofagus* is absent in modern forests of the region. The Butcher's Creek site contrasts with the deep-sea sites in that Araucariaceae is very common and *Nothofagus* rare in the latter, differences commensurate with the comparison of highland forests to coastal lowland forests.

If the Butcher's Creek section is correlated with the Aquarius-1 well site, the abundant *Nothofagus* suggests an early Miocene age, but the disparity between highland and continental shelf sites, respectively, would be large, and the latitudinal difference would make such a correlation dubious. There is little to suggest a correlation between Butcher's Creek and Sites 815 and 823, so that any attempt would be misleading. A substantial body of evidence would be required before any such correlation could be made with confidence.

DISCUSSION

The relatively minor changes through the Miocene–Pliocene sequence are somewhat unexpected. Pollen assemblages from deep-sea sites, however, differ from those on land in that the coastal vegetation is always the vegetation type closest to the site (Fig. 5). At times of low sea level, the coast is relatively close, whereas at times of high sea level, it is farther away. If the vegetation zonation parallels the coast, then the whole zonation may move with changes in sea level, and the same coastal vegetation is always closest to the sites. Vegetation zonation moving in unison with sea-level changes has been shown elsewhere in Australia (Martin, 1973a). A site on land would experience changes in the vegetation, whereas a deep-sea site would register mainly coastal vegetation, be it nearby or far away.

The climate would have remained wet enough to maintain substantial areas of rainforest throughout the time period. Estimated sea surface temperatures are subtropical-tropical through the Neogene (Feary et al., 1991).

The deep-sea sites contrast strongly with those in inland southeastern Australia. Rainforest, the major vegetation type until the middle Miocene, disappeared from most localities during the middle late Miocene, when eucalypt sclerophyll forests became widespread. Rainforest may have remained in small, more favorable habitats, especially close to the coast, where the rainfall was greater than in inland southeastern Australia. Decreasing temperatures and precipitation at the time of the late Miocene lowstand in sea level are thought to have been the causes of the drastic vegetation change in southeastern Australia (Martin, 1987). This change to eucalypt forests did not occur at Sites 815 and 823 of northeastern Queensland, but it did occur at the Aquarius-1 well site.

The location of these sites must be considered in relation to present-day climate (Fig. 6) and vegetation (Fig. 7). Site 823 is offshore of the wettest region in Australia (Leeper, 1970) and the largest area of rainforest (Webb and Tracey, 1981). The Aquarius-1 well site is offshore of a drier region with smaller, more scattered patches of rainforest, and Site 815 is intermediate. The palynology suggests that this differential among the sites existed during the Neogene. Site 823 indicates slightly more rainforest than seen at Site 815. The Aquarius-1 well site, with its substantial Myrtaceae content, suggests that eucalypt

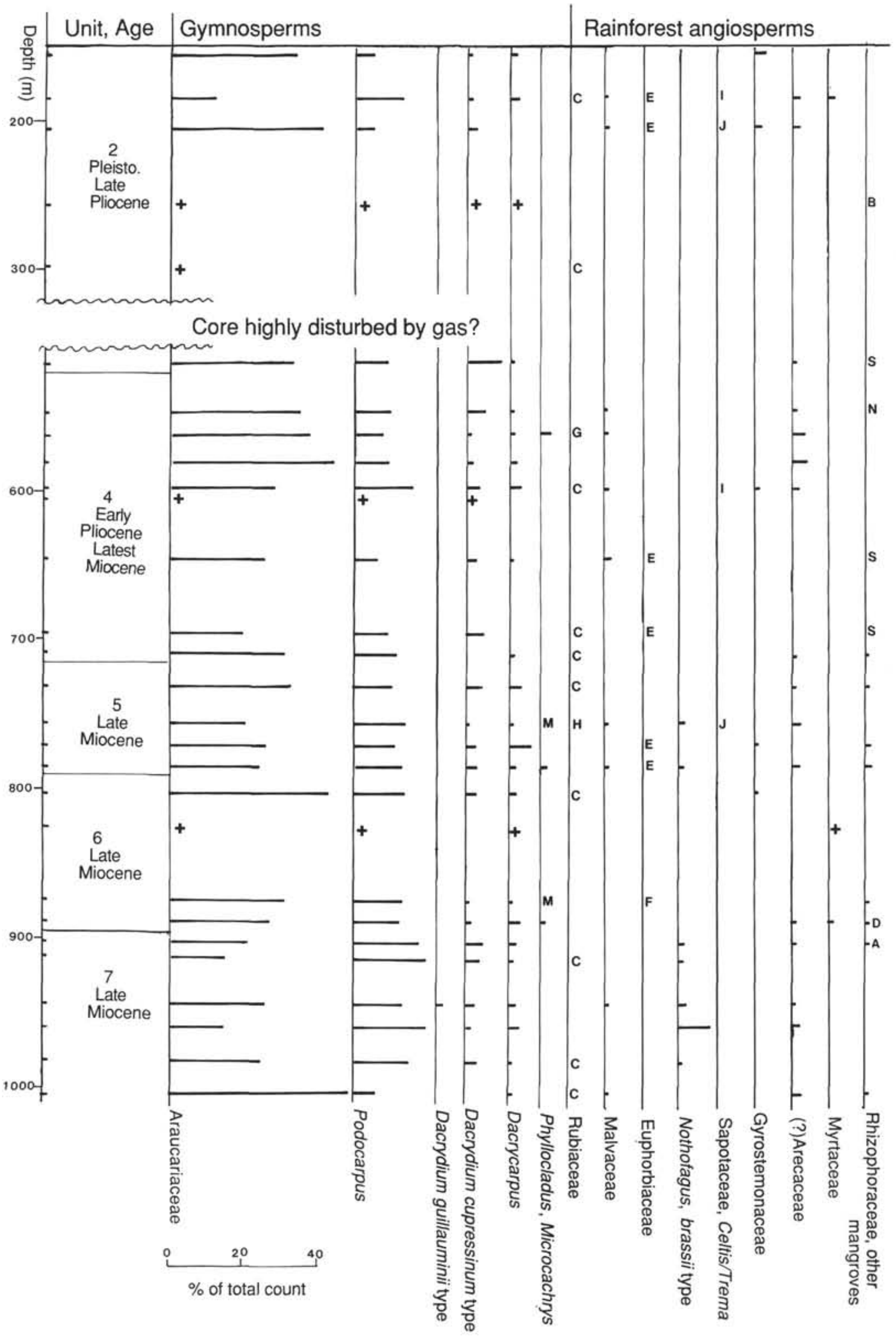

Figure 3. Pollen diagram of Site 823 core. The symbols are the same as those in Figure 2.

forests may have been significant in the landscape of the late Neogene. This differential is determined mainly by topography: the position and height of the dividing range and its influence on onshore rain-bearing winds. Were topography much the same during the Neogene as it is today, and all the evidence indicates that this was the case, then a similar differential would have existed also.

The palynofloras off the northeastern part of the continent are quite different from those off the northwest (McMinn and Martin, 1992). In the northwest, no unequivocal rainforest can be dated to the Neogene. These differences are consistent with the present-day rainfall gradient; northeastern Australia is much wetter than the northwest, and this would have been similar throughout the Neogene.

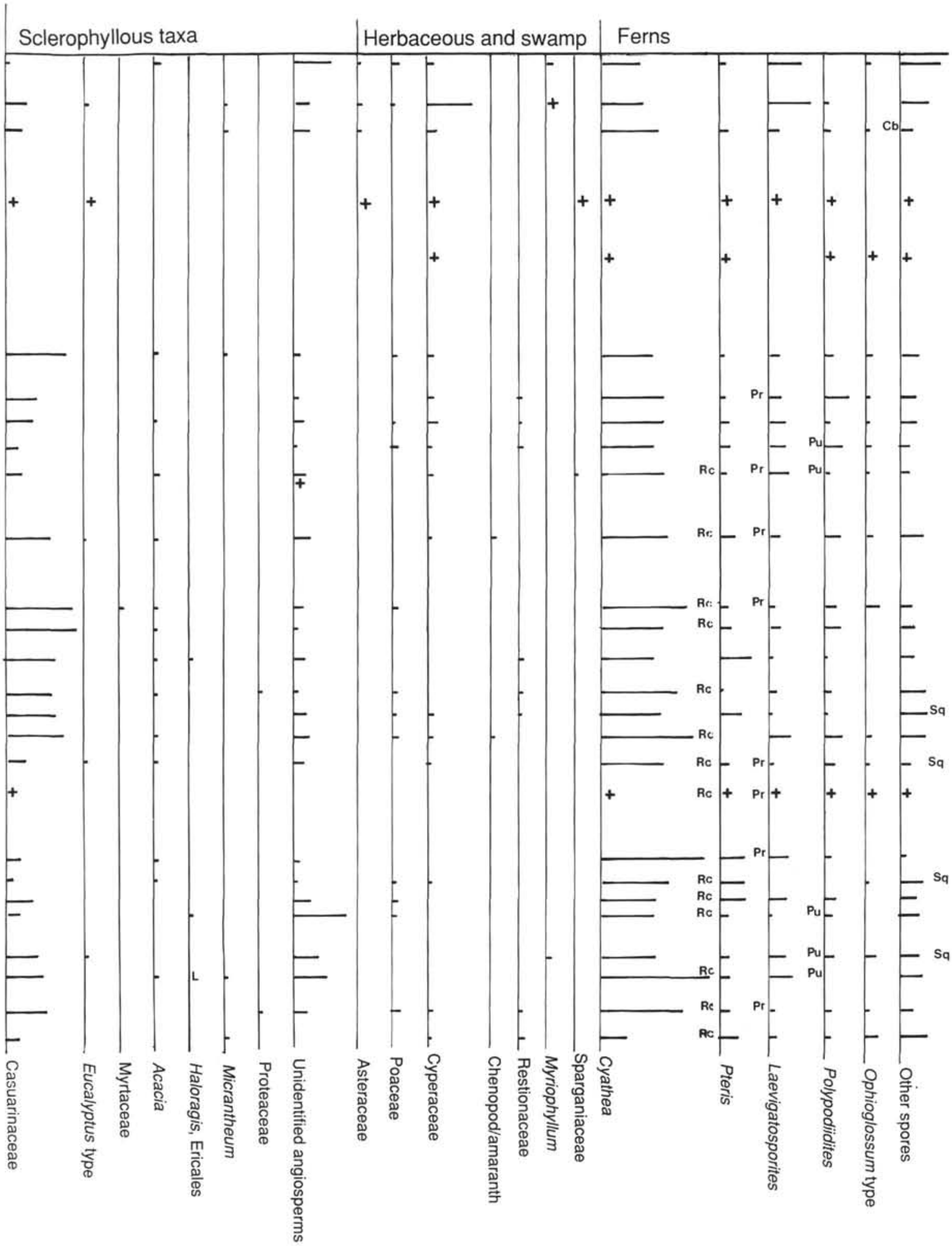

Figure 3 (continued).

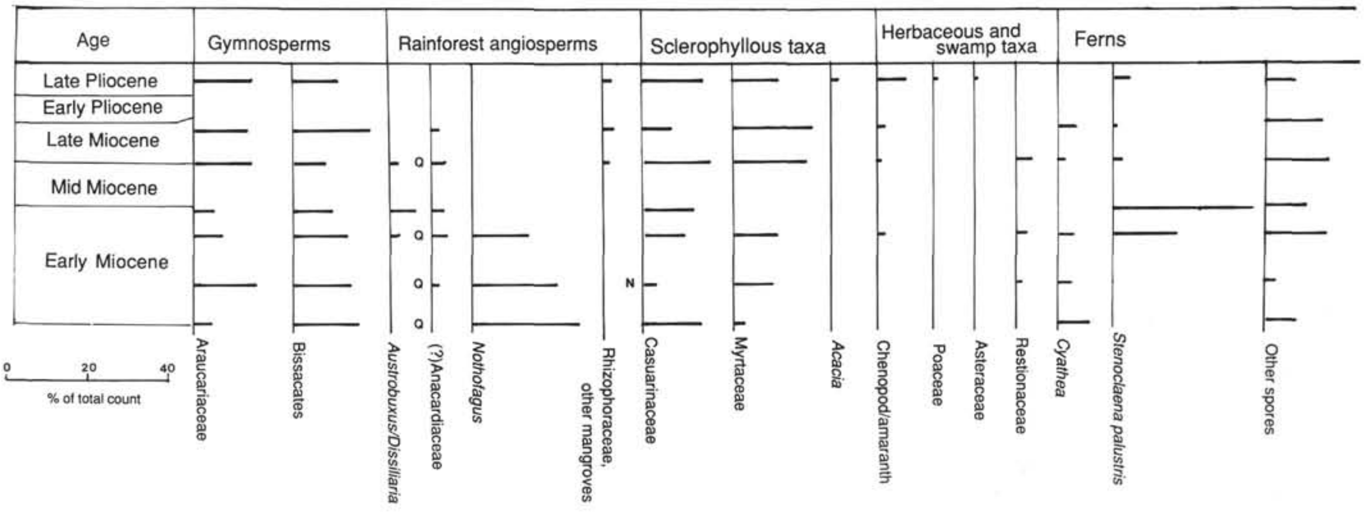

Figure 4. Pollen diagram of A.O.G. Aquarius-1 (from Hekel, 1972). Pollen types are the same as for Figure 2, except that bisaccate pollen includes both podocarps and other gymnosperms. Cyperaceae was not identified.

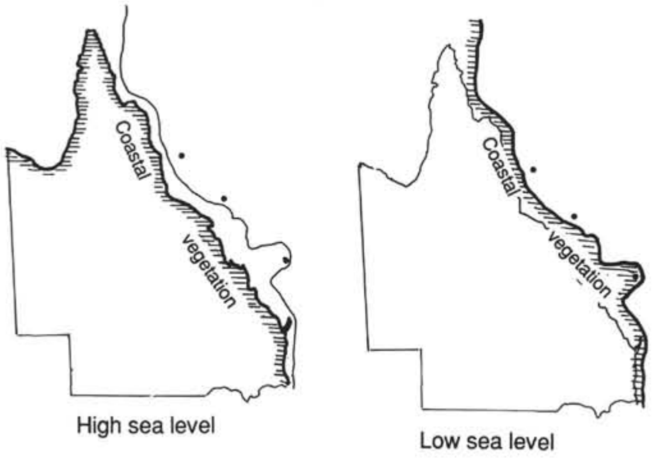

Figure 5. Position of the coastline at high and low sea levels.

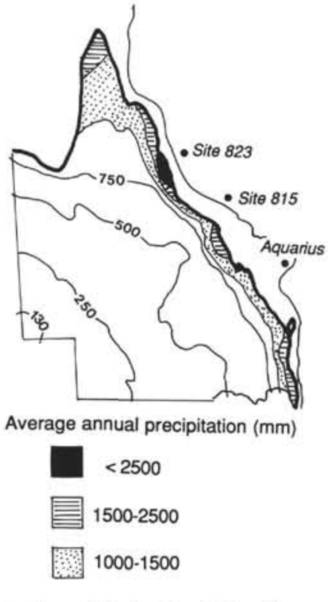

Figure 6. Average annual precipitation (mm) (from Leeper, 1970).

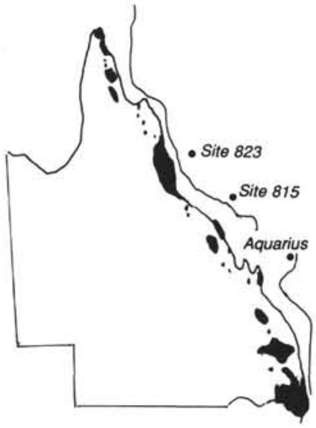

Figure 7. The distribution of rainforest in Queensland. The areas have been exaggerated for purposes of mapping. Many smaller areas in protected gorges are too small to be mapped (from Webb and Tracey, 1981).

Myrtaceae, however, is found infrequently in either the northwest or the northeast.

Northeastern Queensland is renowned for its "primitive" angiosperms. This has led some botanists to place the early evolution of angiosperms in northeastern Queensland, but the fossil record shows that this is unlikely to have been the case. Northeastern Queensland, however, is a refuge for taxa that evolved in earlier time under warm, humid climates. The maintenance of relatively stable, warm and humid climates throughout the Neogene, a time of drastic vegetational change and development of aridity elsewhere in Australia, would have been crucial to the refuge.

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APPENDIX

Pteris Types

An unnamed spore, here identified with *Pteris,* is usually present and may be one of the common spores in the cores.

Plate 1, Figures 1 through 8, shows fossil *Pteris*-type spores. The distal surface has conspicuous verrucae/rugulae. There is a pronounced cingulum with a straight/wavy/lobed edge and a proximal surface with smaller ornamentation, often aligned in patterns following the trilete scar.

Of the modern species surveyed, *P. tremula* (Pl. 1, Figs. 9–11) and *P. umbrosa* (Pl. 1, Figs. 12–13) are similar to the fossil. *P. pacifica* (Pl. 1, Figs. 14–15) and *P. comans* (Pl. 1, Fig. 16) have a similar morphology, but the ornamentation is smaller and more tightly packed and the cingulum more pronounced than on the fossils. *P. papuana* (Pl. 1, Fig. 17), spherical with a small, sparse, granular ornamentation, is unlike the other species of *Pteris. P. vittata* (Pl. 1, Figs. 18–20) has a coarser pattern, with the rugulae forming rough squares around a single verruca. The cingulum is clear on small specimens, but is difficult to see among the very large ornaments on the large specimens. There is an exceptionally large size range in this species (50–100 mm).

Both *P. tremula* and *P. umbrosa* are found in rainforests and damp habitats such as protected gullies of eastern Queensland.

Pteris is a cosmopolitan genus with some 250 species, and probably other spore types can be found in it. Other fossil species have been attributed to the genus, viz *Polypodiaceoisporites usmensis* (Muller, 1968), *Pteris* types A, B, and C (Graham and Jarzen, 1969), *Pteris* types 1 and 2 (Graham, 1987), probably *Cingulatisporites papuanus* and *C. psilatus* (Khan, 1976), and probably more.

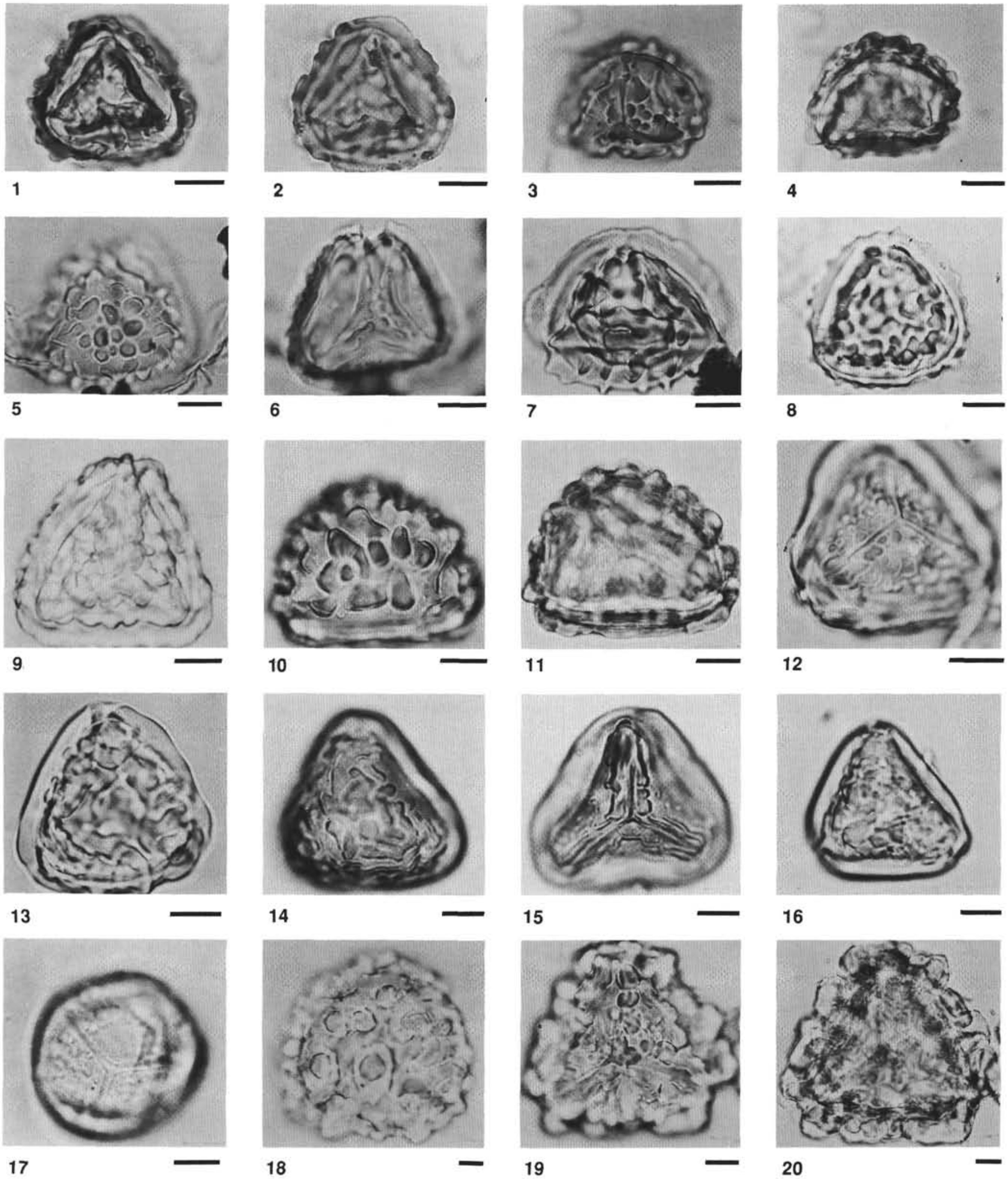

Plate 1. **1–8.** Fossil *Pteris* spores, (1–2) showing verrucae and the cingulum; (3–4) proximal surface, showing pattern aligned along trilete scar and optical section; (5) pattern on the distal surface; (6) proximal surface; (7) oblique view showing verrucae/rugulae; (8) a specimen with a crenate cingulum. **9–20.** Modern *Pteris* spores. **9–11.** *P. tremula,* (9) proximal focus and cingulum; (10–11) equatorial view showing distal ornamentation and optical section. **12–13.** *P. umbrosa,* (12) proximal focus; (13) showing verrucae/rugulae and cingulum. **14–15.** *P. pacifica,* (14) distal sculpture; (15) proximal surface. **16.** *P. comans,* distal surface. **17.** *P. pacifica,* lacking large ornaments and cingulum. **18–20.** *P. vittata,* (18) distal surface; (19–20) proximal surface and optical section, respectively. Scale bars equal 10 μm. Note: Fossil and modern material have received different treatments. Acetolysis, used to remove the spore contents of modern material, swells the spores, whereas the fossils have been treated with hydrofluoric acid, reputed to shrink the spores.