ENIGMATIC HIGH PALAEOLATITUDE
FORESTS OF GONDWANALAND
- A CASE STUDY FROM THE NEW ZEALAND JURASSIC

by

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Volume 1

A thesis
submitted to the Victoria University of Wellington
in fulfilment of the requirements for the degree of
Doctor of Philosophy in Geology

Victoria University of Wellington
1999
Gondwanaland (Gond-wa'-na-land)
var. Gondwana (Gond-wa'-na)

Eduard Suess, an Austrian geologist, named the supercontinent "Gondwana-Land" in 1885 (Das Antlitz der Erde. English translation, 1904). He recognised that a distinctive suite of rocks, containing the *Glossopteris* fossil flora and known as the Gondwana System in central India, was common to all its parts. The literal translation of 'Gondwana' is 'Land of the Gonds' (Gondwanaland' is tautological). The Gonds are a group of Dravidian tribes (>3 million population) inhabiting central India. They are a Hindu race who speak the Dravidian languages of southern India.

The term 'Gondwanaland' is, however, quoted hereafter in the context of Suess' original definition of a former southern supercontinent. The author considers the term 'Gondwana' should be reserved for discussions on the strata of the Indian Gondwana System.

Abstract

Middle Jurassic fossil forest deposits from New Zealand, at a palaeolatitude of ~75-78° South, provide evidence for a diverse vegetation association dominated by Filicopsida and Gymnospermopsida plants. Macrofloral and microfloral studies at present day Kawhia Harbour (North Island) and in the Curio Bay region (South Island) also recognise the preserved remains of Chlorophyta, Bryophyta and Lycopsida and interpret vegetation palaeo-profiles from the fossil flora assemblages. Fossil wood analysis identifies distinct, newly described taxa: Araucarioxylon sp. A, Araucarioxylon sp., Protocupressinoxylon sp. A, Podocarpoxylon sp. A and Protopodocarpoxylon sp..

Facies analysis implies vegetation growth in riverine depositional settings located on merged alluvial fan-toes along the Murihiku basin margin of the south-eastern Gondwanaland coast. Evidence from palaeosols and in-growth-position fossilised tree stumps suggest major floods inundated and destroyed successive forest generations at a minimum recurrence interval of at least 100-150 years.

Interpretations from the distribution and structure of the in-growth-position fossilised tree stumps imply the growth of forests during the Middle Jurassic of varying, but generally high, densities with a distinct vertical structure of undergrowth, canopy and emergent layers. Analysis of fossil wood growth ring widths implies the trees grew rapidly when environmental conditions were favourable and that the forest productivity levels were comparable to those of modern tropical woodlands. Growth ring sequences
studied imply dominantly uniform growing conditions, year to year, with variations possibly reflecting fluctuations in water supply. Rarely, variation in cell widths within individual growth rings suggests growth was disrupted during the first half of certain growing seasons, perhaps also due to changes in water supply or the occurrence of severe storms.

Empirical solar radiation data from 75° North applied to the Middle Jurassic palaeoenvironment and comparison with late-early Permian high palaeolatitude wood from Allan Hills in Antarctica suggests the trees were highly adapted to the near-polar light regime. Wood production was maximised even within the shaded canopy. Climatic parameters interpreted from the sediments and fossil flora suggest a near-tropical, but seasonal, palaeoclimate with wet and warm summers and arid, cool winters. These criteria compare well to simulated Jurassic Global Climate Models for the southeastern margin of Gondwanaland implying model reliability for the prediction of future global temperature trends.
Acknowledgements

I would like to thank my supervisors, Dr. M. Hannah and Prof. P. Barrett (School of Earth Sciences, Victoria University of Wellington (V.U.W.)) for helpful comments throughout and a critical review of this manuscript. Dr. J. Francis (School of Earth Sciences, University of Leeds, U.K.) and Prof. G. Creber (Department of Geology, Royal Holloway, University of London, U.K.) have provided invaluable assistance with the fossil wood analysis and palaeoecology. Thanks are also due to Dr. J. Raine (Institute of Geological and Nuclear Sciences (I.G.N.S.), Lower Hutt) and Dr. N. de Jersey (Greenbank, Queensland, Australia) for help with palynomorph identification. Thanks also to Dr. M. Pole (Department of Botany, University of Queensland, Australia) for forest structure data and discussions on the Curio Bay fossil forest. Thanks also to Dr. B. Hayward and Prof. J. Grant-Mackie (Department of Geology, University of Auckland), Dr. I. Speden and Dr. G. Stevens (I.G.N.S., Lower Hutt) and Prof. C. Landis (Department of Geology, University of Otago) for valuable discussions. Special thanks are also due to Ms. U. Cochran for light relief and a great working environment.

I would also like to acknowledge the research support provided by the technicians of the School of Earth Sciences (V.U.W.), Mr. P. Watson (School of Biological Sciences, V.U.W.), Ms. K. Reader (Electron Microscope Facility, V.U.W.), the V.U.W. Photographic Facility and the V.U.W. Library Reference Department, particularly Mr. Justin Cargill. Permission from the Te Maika Trustees Board (c/o O'Sheas Solicitors, Hamilton) and the Southland Conservancy, Department of Conservation (D.O.C.), to
study the fossil forests at Te Maika Peninsula in Kawhia Harbour and Curio Bay, Southland, respectively, is gratefully acknowledged. In addition, thanks are due to Mr. W. Cooper (Southland Conservancy, D.O.C.) for useful information, photographs and maps of the Curio Bay site. Thanks also to Mr. P. Jury for the use of his bach on Te Maika Peninsula for the duration of fieldwork in winter 1996.

This research has been primarily funded by a New Zealand Vice Chancellors' Committee (N.Z.V.C.C.) Commonwealth Scholarship for which I would like to thank Mrs. M. Penning (V.U.W. Scholarships Officer) and Ms. K. Manuera (N.Z.V.C.C. Scholarships Officer) for administrating and answering my many queries. Fieldwork, overseas conference attendance to present the results from this study and miscellaneous research costs have been greatly aided by grants from the V.U.W. Internal Research Grant Fund and the School of Earth Sciences. Fieldwork in Antarctica was possible as part of an expedition funded by the Swiss National Science Foundation and supported by Antarctica New Zealand.

Finally, I would like to thank my husband Andy for his continual support for everything I do (including fieldwork in the middle of winter!).
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CHAPTER 1

GENERAL INTRODUCTION

1.1 AIMS

One of the more curious features of the geological record, between the late Palaeozoic and Early Tertiary, is the preservation of substantial fossil forests that apparently flourished at high palaeolatitudes during this period. Fossil evidence from the southern supercontinent of Gondwanaland, prior to its fragmentation beginning approximately 200 Ma (Lawver, et al., 1992), suggests a cosmopolitan vegetation cover consisting dominantly of Gymnospermopsida (mainly conifer-related plants) and Filicopsida (ferns). This study concentrates on two fossil forest deposits from the Middle Jurassic of New Zealand and aims to further knowledge on Gondwanaland forest ecology and climate.

The two fossil forest deposits investigated are located at Kawhia Harbour, in the Waikato region of North Island and Curio Bay, in the Southland region of South Island, New Zealand. Both localities were situated on the Gondwanaland supercontinent at high palaeolatitudes of 75-78° South (Section 1.32, p. 49). The strata contain well preserved fossilised tree trunks, stumps, fossilised leaves, spores, pollen and other miscellaneous fossil plant organs. The growth patterns of fossil wood from the Middle Jurassic fossil forests of New Zealand will be compared with those of fossil wood (not preserved in-
growth-position) collected by the author from Allan Hills nunatak in the Transantarctic Mountains. Allan Hills is considered to have been located at a similar palaeolatitude in the Permian as it is today at 80° South.

Currently, the southern latitudinal limit of conifer tree growth is coincident with the lowermost tip of South America at approximately 55° South (Creber and Chaloner, 1984b). However, several fossil wood sites have been discovered in palaeolatitudes of >55° South, in Gondwanaland strata dating from the Permian through to the Upper Cretaceous (Figure 1.1 and Table 1.1). Flora on mainland Antarctica today includes fungi, algae, lichens, liverworts, bryophytes and only two species of flowering vascular plants: *Colobanthus quietensis* (Kunth) Bartl. (a herb) and *Deschampsia antarctica* Desv. (a grass) (Ahmadjian, 1970). The lichens reach closest towards the Pole and have been found at 86° South in the Horlick and Queen Maud Mountain ranges (Lamb, 1970). Snow algae are also found on the Antarctic Ice Sheet, but the remainder are mostly restricted to the Antarctic Peninsula or coastal areas (*ibid.*).

In general, this inquiry draws interpretations about the palaeoecology, palaeoenvironment and palaeoclimatology of the south-east Gondwanaland margin in the Middle Jurassic from the New Zealand sedimentary and fossil flora record. Facies analysis and observations on contemporaneous units exposed in the regions surrounding the study sites will provide the basis for an interpretation of the depositional environment and regional palaeogeography, including the extent of vegetation cover, locality of the coastlines, palaeoslope and sediment source. Fossil macroflora and
Figure 1.1  Selected localities of fossil wood discoveries within Gondwanaland at palaeolatitudes > 55° South (inner circle). Sites listed in Table 1.1. Highlighted sites are studied in this thesis; (a) and (b) after Lawver, et al., 1992, (c) after Lawver and Scotese, 1987.
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<td>Not stated</td>
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<td>Plumstead, 1975.</td>
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microflora provide evidence for the source vegetation community composition, as well as the vertical structure and distribution of the original forest stands. A taphonomic analysis of the well-preserved Kawhia Harbour fossil forest horizons allows the definition of taphocenoses\(^1\). This process provides a basis for the reconstruction of the vegetation once growing in the region of this locality. The Curio Bay locality is not suitable for a detailed taphonomic analysis due to a short measurable stratigraphic section (Section 2.3), poor fossil flora preservation and a low quantity of collectable material.

Growth ring width sequences from fossil wood indicate the reaction of trees growing in the geological past to the palaeoclimate and palaeoenvironmental variables (for example, water and nutrient supply). The climatic regime prevalent at 75-78\(^\circ\) South in the New Zealand Middle Jurassic can be broadly interpreted from this information. A comparable study of the Permian high palaeolatitude wood from Allan Hills, Antarctica, will determine whether the polar light regime affected the growth pattern of these trees in a similar manner to those from the Middle Jurassic.

In conclusion, models of the palaeoenvironment, palaeoclimate and palaeoecology in the New Zealand Middle Jurassic, interpreted from the sedimentary and palaeobotanical record, will be formulated and compared to Global Climate Models (G.C.M.s) simulated for the Jurassic. The new climatic data interpreted from the fossil record can then be used in the rationalisation of the value of G.C.M.s for the prediction of future global

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\(^1\) A repeatable group of dispersed fossil organs occurring within a particular sedimentary facies (after Krasilov, 1975).
climate patterns.

In summary, the aims of this study are:

- To contribute to the understanding of the enigma of widespread fossil vascular plant vegetation in the polar region where the climatic regime of today allows only very restricted forms to exist.
- To create ecological models for the New Zealand Middle Jurassic high palaeolatitude forests.
- To create a broad climatological model for the New Zealand Middle Jurassic with the aim of testing Mesozoic G.C.M.s and their value for future climate prediction.

1.2 PREVIOUS WORK

1.21 The Debate on High Palaeolatitude Floras

Late Palaeozoic to early Cenozoic strata containing fossil leaves, wood and palynomorphs suggest a sub-tropical to temperate climatic regime up to palaeolatitudes of ~85° North and South (for example, Douglas and Williams, 1982). Modern analogues of prolific vegetation at such latitudes are conspicuously absent due to the limitations of temperature and extreme light variability throughout the year which restricts such floras to a much lower latitudinal belt.
The recognition of a diverse, mainly floral, fossil record at high palaeolatitudes has prompted several possible explanations. In general, the theories proposed suggest mechanisms by which current polar conditions could have been altered to support plant growth at high latitudes in the past. Table 1.2 lists current hypotheses based on astronomical and palaeogeographical changes in the Earth's system. Overall, these would result in milder temperatures, more uniform diurnal light and dark periods and shorter seasonal polar days and nights at high palaeolatitudes. These temperature and light conditions could support plant growth much closer to both Poles than in today's configuration assuming that plant habitat preferences, in general, have not changed significantly over geological time.

Table 1.2 Hypotheses based on astronomical and palaeogeographic changes to the Earth to explain the presence of high latitude floras in the geological record.

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<td>Palaeogeographical Changes</td>
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<td></td>
<td>Increase in global temperatures due to</td>
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No one theory is without uncertainty and a combination of several mechanisms could explain high palaeolatitude plant growth. The following section describes each
mechanism listed in Table 1.2 in more detail and provides an overview on the current status of discussion on these enigmatic high palaeolatitude floras. Specific factors of high latitude light regimes and their limitations on modern plant growth are also discussed.

_Astronomical Changes_

**Reduction in the Earth’s obliquity**

The Earth’s obliquity is the tilt of the rotation axis, from vertical, in the ecliptic plane and is presently at 23.5 ± 1.5° (Douglas and Williams, 1982) (Figure 1.21(a)). This current angle of tilt causes the length of day and night to vary significantly throughout the year in the high latitudes. Poleward of the Polar Circles (66.5° North and South), the Earth’s surface undergoes periods of continual darkness and light throughout the year (the _Polar Night_ and _Polar Day_), in comparison to the more uniform diurnal cycle of the lower latitudes. The latitudinal distribution of modern plants today is limited mainly by seasonal temperature ranges and also by photoperiod, resulting in a short high latitude growing season (Axelrod, 1984). Even with warmer temperatures in the polar regions than today, plants would require physiological adaptations to cope with the imbalance of photosynthesis and respiration caused by the large variation in photoperiod throughout the year (p. 13).

A substantial reduction in axial obliquity in the geological past was postulated as a
Figure 1.21  The arrangement of the Equator, Tropics and Polar Circles of the Earth at varying obliquities to the axis of the ecliptic ($\alpha$) at noon on the southern Summer Solstice (December 21st). Axis of rotation: $\beta$; Arctic Circle: Arc; Tropic of Cancer: Can; Equator: Equ; Tropic of Capricorn: Cap; Antarctic Circle: Ant.
mechanism for providing a more equable light regime in high palaeolatitudes. Obliquity’s ranging from near zero (Allard, 1948) to 15° (Wolfe, 1977, 1978, 1980; Xu Qinqi, 1980) (Figure 1.21(b)) were suggested, and in combination with an increased Equator-Pole temperature gradient (perhaps caused by a different mechanism), would provide adequate growing conditions closer to the Pole (Douglas and Williams, 1982). Creber and Chaloner (1984a) agreed that a reduced obliquity would diminish the temperature extremities between the polar summer and winter and that daily periods of sunlight and darkness would be more equable. However, based on early work by Darwin (1879) on the Earth-Moon system, they consider only 1° variations in tilt may have occurred over Phanerozoic time. Such minor fluctuations would be easily masked by the Milankovitch Cycles and are far less than the required modification to substantially alter the light regime. Finally, Barron (1984) demonstrated by computer modelling that a lower obliquity would result in levels of sunlight at the poles to low for the survival of vegetation, thereby negating the reduced obliquity hypothesis.

**Increase in the Earth’s obliquity**

Williams (1972, 1973, 1975) proposed an *increase* in the Earth’s obliquity resulting in raised temperatures and increased biological productivity, due to a higher proportion of steeper incident sunlight in temperate and polar regions during the summer months (Figure 1.21(c)). However, productivity would be affected by many other factors, including the highly inequable light regime and temperature extremes of such a configuration. Few authors have explored this scenario further (refer to discussion in

Increase in the Solar Constant

McKenna (1980) suggested an increase in the Solar Constant during the Cenozoic could help explain a formerly warmer and more equable Arctic climate during this time. The Solar Constant is the amount of solar energy received by the Earth. Therefore, increased energy receipt at high palaeolatitudes could well explain the rise in temperature required for plant life to survive in the polar regions. However, there is a lack of contemporaneous evidence of very high temperatures in the lower latitudes.

*Palaeogeographical Changes*

Poleward continental drift

Mechanisms of true polar wandering (Evans, 1876; Geikie, 1882; Wegener, 1924), or later, continental drift (Campbell, 1942) were suggested to have caused vegetated continental fragments, originally located at lower latitudes, to move poleward subsequent to the preservation of a substantial flora within their sediments. Hypotheses of this nature were advocated to explain the Antarctic fossil flora (Plumstead, 1964; Cranwell, 1969), but more recent palaeomagnetic and sea floor spreading data places Antarctica in a near-polar position for much of the Phanerozoic (Smith, et al., 1981) (Figure 1.22).
Palaeolatitude estimates for continental fragments, based on palaeomagnetic data, rely on the assumption that the Earth’s Magnetic Pole has been closely related to the Geographic Pole throughout the geological past. Jefferson (1983) considers this a likely scenario as a close association between the two poles could be expected when averaged out over millions of years. Further, it is generally assumed by the geophysical community that the average orientation of the main dipole field coincides with Earth’s rotation axis. This is referred to as the *Axial Geocentric Dipole Hypothesis* and is the basis for all reconstructions using palaeomagnetic pole positions (Turner, pers. commun., 1998).

**Figure 1.22** Magnetic polar wandering curve for the Antarctic region over the last 400 million years. After Barrett, 1991.

**Increase in global temperatures due to continental proximity**

It has been argued that even with successful adaptations to the high latitude light regime
only raised temperatures could have permitted successful vegetation growth in the near-polar regions (Haughton, 1878; Berry, 1929).

Global climate simulation models for the Cretaceous suggest that the proximity of landmasses at that time may have raised global temperatures forming a warmer and wider low latitude belt than today (Barron, et al., 1981; Barron and Washington, 1982, 1984; Barron, 1983) (Figure 1.23). Furthermore, increasing the atmospheric CO$_2$ parameter in models based on modern geography, causes a reduction in the Equator-Pole temperature gradient (Berner, et al., 1983; Barron and Washington, 1984). In combination with a reduced obliquity (to $-5$-$15^\circ$) this could well have aided high latitude plant growth during the Mesozoic (Douglas and Williams, 1982). In the polar regions, evaporation and precipitation would rise in parallel with temperature and CO$_2$, which could only have been beneficial for photosynthetic rates and plant productivity (Francis, 1986).

*Limitations of the High Latitude Light Regime on Plant Growth*

Assuming the polar regions were significantly warmer during periods of the geological past, plants would still have had to cope with the radically different light regime inherent at high palaeolatitudes. Our knowledge of modern plant biology suggests that physiological adaptations would be required to enable vascular plants to survive.

During the Polar Night, and at adequate temperatures, evergreen plants would respire to
death in the absence of light by depleting their food supply (Mason, 1947). Trees may have been deciduous (Plumstead, 1958; Francis, et al., 1994), had complete metabolic shutdown during the polar night (Axelrod, 1984) or may have developed as photoperiodic ecotypes (Vaartaja, 1962) to cope with the prolonged darkness.
The low angle of incidence of the solar rays at high latitudes reduces the efficiency of light interception by tree crowns in a dense forest stand. Jefferson (1982) measured ingrowth-position fossil tree stump spacing within the fossil forest floor horizons exposed at Alexander Island (Figure 1.24), west of the Antarctic Peninsula, from a palaeolatitude of 65-75° South. He concluded that given an adequate temperature and conical crown shape, net productivity could be maintained for an individual tree, despite the mutual shading of the surrounding stems.

Figure 1.24  Diagrammatic reconstruction of a fossil forest floor at Alexander Island, Antarctica. Stump position and size as measured. After Jefferson, 1982.

Additional factors relating to the polar light regime are the length of the growing season and the rate of solar radiation reaching the Earth's surface. Neither should be limiting to plant growth at high latitudes (Ford, et al., 1978; Warren Wilson, 1966). Therefore, it is apparent that, with an adequate temperature, vascular plants in the geological past could well have adapted in several ways to be capable of net productivity in the variable light
regime of the high palaeolatitudes.

In summary, discussion on possible solutions for explaining the presence of the high palaeolatitude fossil floras has occurred for decades and despite intensive research cannot yet be satisfactorily explained. Empirical studies on modern floras have provided evidence of mechanisms by which vascular plants in the geological past could well have adapted to the high palaeolatitude light regime (for example, Vaartaja, 1962). However, there are no naturally growing modern examples for comparison. The growth patterns and physiology of fossil trees and associated fossil flora from the Jurassic of New Zealand will be studied in the following chapters. Quantifiable techniques will be used and comparisons made with Antarctic Permian fossil wood and modern related flora. The amount of net productivity in the Jurassic high southern palaeolatitudes, assuming a similar light regime to today and regardless of temperature, will then be estimated. The hypotheses discussed in the previous section can then be reviewed as to their suitability for explaining the results achieved.

1.22 Fossil Forest Deposits as Palaeoenvironmental Tools

Analysis of in-growth-position fossil forest ecology involves many avenues of investigation. For example, taxonomy, fossil tree spacing and density, community structure and succession can be related to the depositional environment and the palaeoclimate. If the deposit contains a diverse, well preserved assemblage, then many types of fossil plant organs can be examined, including fossilised wood (tree stumps still
in growth position or material no longer in growth position (*ex situ*), leaf impressions, fruits, seeds or palynomorphs. Each group provides a different perspective on the forest ecology and contributes to the interpretation of the palaeoenvironment.

The following section discusses the derivation of palaeoenvironmental information from the different fossil plant organs. Gymnosperm-dominated floras are considered exclusively because angiosperms did not evolve until the early Cretaceous and are not found in the assemblages discussed in this study. Environmental and non-environmental factors acting on modern trees during growth can be used to interpret palaeoclimatic information from well-preserved fossilised wood. If trees have been preserved in their original growth position, important information can be interpreted about the ecology of the fossil forest. Fossil leaves and terrestrial palynomorphs can provide additional local and more regional information, respectively, on the vegetation community and habitat. Factors relating to the taphonomy (the post-mortem history of the organic remains) and assumptions relating to the preservation, exposure and physiology of the fossilised flora must also be considered before interpreting these assemblages.

*The Palaeoenvironmental Record in Fossilised Wood*

Unger (1847) was the first to derive palaeoclimatic interpretations from fossil wood fragments. He postulated a climate without seasons in the Palaeozoic from the absence of growth rings. Further investigations by later authors were more cautious, recognising the difficulties in making direct climatic interpretations in this way (for example,
The issue has since been reviewed by many (for example, Frentzen, 1931; Antevs, 1917, 1925, 1953) and mentioned by others (for example, Arnold, 1947; Kräusel, 1961, 1964), but remains controversial (Chaloner and Creber, 1973) due to the large number of influencing factors.

Growth ring sequences were observed in many of the permineralised tree fragments in the present study from the Middle Jurassic and the Permian (for example, Plates 13 and 17). They form in the secondary xylem of woody plants and provide an excellent high resolution record of annual environmental conditions over several consecutive years during the plant’s life. The process of growth ring formation and the overall histology of wood is outlined in Section 4.23. In temperate latitudes, each ring usually represents an annual increment of growth, although this is not always the case (p. 26).

Growth ring morphology is the result of influence by both non-environmental (or internal) factors and environmental (external) factors on the living tree. To interpret the palaeoclimatic signature from growth ring sequences it is necessary to exclude the internal effects. The features caused by environmental influences alone can then be recognised and broad inferences drawn about the palaeoclimate. Details of the specific influencing factors and their effects on growth ring characteristics are discussed in Section 4.23. Fossil wood characteristics particularly useful for palaeoclimatic interpretation have been identified in a scheme published by Chapman (1994) and are summarised in Section 5.1.

1 The Plates can be found at the end of Volume 2.
2 Vascular tissue following the formation of primary xylem.
In-growth-position Fossil Tree Stump Horizons

Fossilised tree stumps preserved in sediments at the tree’s original growth site have been found throughout the world (for example, Jefferson, 1982; Francis, 1988; Mosbrugger, et al., 1994; this thesis). The distribution and size of the fossilised stumps at a particular horizon, plus the growth ring data, provides direct evidence for the structure and ecology of the original forest. Fossil stump spacing can be used to estimate original tree density and tree height (including canopy development) can be interpreted from trunk diameters. Vegetation dynamics (biomass production and net wood productivity) can also be estimated from well-preserved growth rings and compared with modern forests.

Palaeoclimatic Interpretations from Fossil Flora Organs, other than Fossilised Wood

Quantification of climatic characteristics (for example, temperature, humidity and precipitation) is very difficult from palaeobotanical assemblages. Palaeoclimatic interpretations of pre-Cretaceous plant fossil assemblages do not have the benefit of angiosperm leaf forms (Crabtree, 1987; Upchurch and Wolfe, 1987) or wood (Carlquist, 1975, 1977), so are derived from our knowledge of the habitats and distribution of modern plant relatives.

Regional palaeoclimate may be estimated using the terrestrial palynomorph record. For example, a positive correlation has been found between Classopollis (= Corollina) pollen content and palaeotemperature measurements in Cretaceous sediments of the USSR (Vakhrameev, 1978) (Figure 1.25). A rising content of Classopollis also
indicates increasing aridization (Meyen, 1987). Further, by assuming that the environmental preferences of plant groups have not changed significantly over time, ancient terrestrial palynomorph form genera can be compared with similar modern spores. The habitat of the modern plant can then be extrapolated into the fossil record. For example, Stereisporites spp. (Plate 29, Figures 3-5) can be compared with sphagnum moss spores which imply very wet soil conditions and high rainfall. Therefore, the entire fossil assemblage can allow broad interpretations about the palaeoenvironment and palaeoclimate with reference to the known habitats of related modern groups.

![Graph showing correlation between palaeotemperature measurements and Classopollis (= Corollina) pollen content in the Cretaceous of southern regions of the USSR. Vertical axis - relative pollen abundance (%) and temperature (°C); horizontal axis - Cretaceous stages from Berriasian to Turonian. 1, Middle Asiatic seas; 2, Turkmenia and Uzbekistan; 3, SE Caucasus; 4, Crimea. After Vakhrameev, 1978.](image)
Fossil Flora Taphonomy

Mode of dispersal and deposition

The mechanisms of dispersal of the different floral organs found in fossil plant assemblages determine their method of incorporation into the sediment. It can be difficult to differentiate between local, extralocal and regional influx of preserved plant material. This is important for the reconstruction of vegetation communities. Therefore, the value of autochthonous wood deposits remains unsurpassed for the reconstruction of local vegetation.

Fossilised leaves and fruit/seed assemblages are dispersed from the canopy by wind, followed by often minor transport in water, before becoming embedded in clay or silt sediments in calm water (Van der Burgh, 1994). This low energy transport and deposition preserves these predominantly local/extralocal plant organs relatively intact. Terrestrial palynomorphs and loose wood debris, in contrast, give an indication of the composition of the regional vegetation¹ (Lange, 1982).

In addition, taphonomic bias may be considerable when estimations are made on the composition and relative abundance of taxa from a leaf flora or palynofloras (Mosbrugger, et al., 1994). Palynology, for example, is limited due mainly to over-representation of wind-polllinated species, poor representation of species with fragile

¹ Despite the limitations of its weight and bulk, wood can float for some time in rivers before becoming waterlogged.
pollen and the impossibility of resolving taxa with conservative pollen types (Holden, 1983).

**Mode of burial and preservation**

The process of burial may compact the cellular structure of wood, prior to fossilisation, thereby altering the original cell diameters and consequently the ring widths and stump diameters. Badly distorted cellular structure is useless for palaeoenvironmental interpretation, but completely uncrushed fossil wood is rare. Calculated adjustments are made during measurement on minimally crushed specimens in this study (Figure E1, Appendix E).

Taphonomic processes tend to detach the different organs of a tree (roots, stump, trunk, branches, leaves, etc.) which are preserved separately in the sediments. The growth ring pattern appearance is different in each woody organ, so when studying a particular piece of fossil wood it is important to recognise which it represents in order to draw interpretations. Chapman (1994) discussed the recognition of the different woody tree organs from the appearance of the growth rings (Section 4.23).

*Fossil Forest Analysis Assumptions*

Much of the information derived from all aspects of the fossil flora in the fossil forest horizons requires the use of modern analogues to model the unknown factors of the geological past. This principle of uniformitarianism becomes difficult when
extrapolating back to the Mesozoic. For example, the ecological preferences of some groups may have changed significantly over time. However, if all factors, prior, during and after fossilisation, influencing the palaeoenvironmental signature of the flora are taken into consideration during collecting, investigation and subsequent interpretation, then the wealth of information provided by such a fossil floral assemblage can be utilised.

The following section discusses the main assumptions necessary when studying fossil forest assemblages, related to the field mapping and preservation of the fossil tree stump horizons and their subsequent interpretation.

Field Mapping and Preservation

When mapping a specific fossil tree stump horizon, various assumptions must be made on the completeness of the preservation and the ambiguity of certain field observations. For example, it must be assumed that the preserved stumps are representative of the entire population of trees over the observed area of fossil forest floor. Different tree species may have significantly different fossilisation potentials which may result in an underestimation of the forest density in life. In addition, the extent to which wood characters themselves influence preservation is relatively unknown (Woodcock and Ignas, 1994). Casts or concretions of radiating fossilised roots often indicate the presence of trees that had not been fully preserved, so in the absence of these features it can be assumed that the entire tree population at that site is represented.
The measured diameters of the fossilised stumps are most likely to be less than they were in life, due to the usual decay of bark and phloem prior to fossilisation and compaction on burial (Francis, 1988). Consequently, biomass production calculations, tree height estimations and subsequent interpretations are all affected. A further preservation issue causes mapping problems with the discovery of small upright stems within the fossil forest floor. These may be either in-growth-position fossil shrub-sized stumps or ex situ branches which have fallen from the canopy and become embedded in the palaeosurface. To overcome this uncertainty, many authors disregard stems <8.0 cm diameter (Mosbrugger, et al., 1994; Pole, pers. commun., 1996), using the modern forestry definition of a tree being >7.5 cm diameter at breast height (Mosbrugger, 1990). This procedure is adopted in this study.

Mapping the spacing of the fossilised stumps in any one horizon may inaccurately reflect the living forest density if, for example, some of the trees were dead when buried. The dead trees would still take up space in the forest, but mutual shading of living trees would be minimal (due to the lack of foliage) and there would be no local competition for nutrients or water. The possibility of including dead tree material artificially increases the interpreted biomass production for the forest, based by necessity on all of the stumps recorded. In addition, by ignoring stems <8.0 cm in diameter, palaeoecological reconstructions are limited by under-representing the shrub layer in the vegetation community. Such plants, plus herbaceous vegetation, are recognised within the palynological preparations, but information on distribution patterns cannot be derived.
A further difficulty with fossil forest floor horizons exposed parallel to the erosion surface is the differentiation between in-growth-position fossil stumps growing from the observable palaeosol and those protruding from one below (Figure 1.26). This can result in an overestimation of forest density at any one horizon. The irregular circumference outline characteristic of stumps, incorporating the exit of main roots from the trunk base, is usually observed close to the palaeosurface and can be sufficient to place all those mapped at a contemporaneous horizon.

Figure 1.26  Schematic representation of trees growing on successive forest floors to illustrate that the sampling surface under investigation (plane A) includes axes from underlying horizons. After Mosbrugger, et al., 1994.

Tree Physiology

In addition to considerations during fossilised tree stump horizon mapping, the interpretation of the results can also be affected by certain assumptions. For example, it
is assumed that the physiology of all the fossilised trees was the same in life. However, this does not account for probable differences between or within taxa. Further, the physiology of a particular species may be altered in different growing environments (Woodcock and Ignas, 1994). This assumption has ramifications for the analysis of growth rings and all subsequent interpretations. When attempting to determine the effect of taxonomy or depositional environment on growth patterns, difficulties occur when only small numbers of specimens are found. This may artificially enhance the effect of minor histological variations attributable to physiological differences. Further, growth pattern analysis is hindered if preservation is not good enough to allow taxonomic determination, and if comparable in-growth-position fossil assemblages, of similar age and taxonomic composition, in different sedimentary environments cannot be found.

It is also generally assumed that the presence or absence of growth rings in fossil wood is an indication of seasonality in the climate. However, this may not be an accurate assumption (Creber and Chaloner, 1984b; Woodcock and Ignas, 1994). Taxa in a modern mixed forest in the tropics have varied wood growth patterns (Tomlinson and Craighead, 1972) and may or may not produce rings. Some trees are known to only produce rings in relation to the rainfall pattern, for example, *Diopyros*, a mangrove in Northern Queensland (Duke, et al., 1981). Further, false rings may form due to leaf flushes and frost rings by severe late frosts, pests or fire damage. However, these zones of abnormal cells are distinguishable from true annual growth rings at the microscopic level.
Summary

Fossil floral assemblages provide a complex body of data from which to derive palaeoenvironmental and palaeoclimatic information. However, by recording the appropriate features of the fossil flora and recognising the limitations of the interpretations, sound models of the vegetation community can be derived. The enclosing sedimentary facies can then be used to relate forest depositional environment to inferred palaeogeography and palaeoclimate.

1.3 LOCALITIES AND GEOLOGICAL SETTING

1.31 Introduction

To formulate realistic palaeoecological models of fossil forests an abundant, diverse and well preserved fossil floral assemblage, preferably of local or extralocal origin is necessary. Further, the geological setting and exposure of the site must allow the observation of fossil tree stumps, in-growth-position and rooted in the same palaeosurface, over a wide area. Metamorphism of the sediments must also be minimal to retain the original spacing, shape and cellular construction of the fossilised wood.

Two fossil forest localities, one at Kawhia Harbour in the North Island, and the other at Curio Bay in the South Island, are found in the Middle Jurassic strata of New Zealand,
and meet these requirements. They are both in well-exposed sedimentary sequences, metamorphosed up to only zeolite facies. Additional fossil wood (not preserved in-growth-position) studied from the late-early Permian of Allan Hills in the Transantarctic Mountains, has undergone only minimal burial metamorphism. An introduction to the palaeobotany and geological setting of the study sites, in the following section, explains their geological relationship and significance for this study.

1.32 New Zealand Localities

_Kawhia Harbour, Waikato, North Island_

The primary site of investigation for this study is located on Te Maika Peninsula, a northward-projecting promontory in the mouth of Kawhia Harbour, on the west coast of North Island (Figure 1.31(a); Figure 1.32). Here, relatively steeply (mean dip = 39°) eastward-dipping sandstone, conglomerate and siltstone crop-out on the shore platform and cliffs, exhibiting many horizons of fossilised tree stumps, still in-growth-position (Figure 1.31(b)). The fine-grained beds contain leaf and other fossil macrofloral detritus and diverse terrestrial palynomorph assemblages. Along strike, on neighbouring Totara Peninsula (Figure 1.32), further fossil forest floor horizons are exposed with an abundant collection of _ex situ_ silicified wood material, originating from the same strata. The fossil flora-bearing strata at Te Maika and Totara Peninsulas were first described in detail by Fleming and Kear (1960) and named the Urawitiki Measures. This is the oldest formation of the Middle Jurassic Rengarenga Group, within the Murihiku Supergroup.
Figure I.31  (a) Locality map of primary study site: Kawhia Harbour, Waikato, North Island, New Zealand.  
(b) Example of an in-growth-position fossilised tree stump at this locality. Clast = 8 cm wide.
Figure 1.32  Map and cross-sections to show the regional geology and structure of Kawhia Harbour, North Island. Modified from Waterhouse and White, 1994.
Regional Structure

Triassic-Jurassic strata crop-out within the Kawhia Regional Syncline (Suggate, 1978) parallel to and 35 km inland of the coastline in the Kawhia region, over a distance of ~150 km. The syncline formed by large scale folding and associated faulting during the early Cretaceous Rangitata Orogeny. There has been no further significant deformation since this time. Upper Triassic - Upper Jurassic sediments, south of Kawhia Harbour and on the western limb of the Kawhia Regional Syncline, strike approximately north/south and dip relatively steeply (approximately 30-40°), either due west or east, relative to the positions of major north/south striking subsidiary folds (Figure 1.32). The Rengarenga Group, at Te Maika and Totara Peninsulas, crops-out on the western limb of the Toe Syncline-Fault, on the western flank. Major faulting along the axis caused several hundred metres of vertical displacement.

Local Stratigraphy

The Urawitiki Measures consist of 520 m of carbonaceous beds that crop-out from just south of Otoretaitua Point on the tip of Te Maika Peninsula, eastwards around the coast to slightly west of Totara Point, on Totara Peninsula (Figure 1.33). The lower boundary of the Urawitiki Measures with the underlying Opango Formation of the Newcastle Group lies buried beneath recent dunes between Ururoa and Otoretaitua Points, on the west coast of Te Maika Peninsula.
Figure 1.33 Map of Te Maika and Totara Peninsulas in Kawhia Harbour to show the distribution of the Middle Jurassic Rengarenga Group formations, particularly the fossil forest-bearing Urawitiki Measures, studied in this thesis. Geographical localities referred to in the text are also clarified. Modified from Waterhouse and White, 1994.
The Opapaka Sandstone, which overlies the Urawitiki Measures, represents a brief marine incursion into the region, followed by a further terrestrial formation, the Wharetanu Measures. The latter contains rare fossilised tree stumps and carbonaceous debris and is the uppermost formation of the Rengarenga Group. Coeval strata containing carbonaceous plant debris and occasional fossil wood have also been recognised in the Albatross Point fault-block to the west (Figure 1.32). However, it has not been possible to correlate these with the formations of the Te Maika Peninsula area (Martin, 1975). On the east flank of the Kawhia Regional Syncline, a further group of predominantly marine Middle Jurassic sediments have also been described (Fleming and Kear, 1960; Waterhouse and White, 1994).

Age

Fleming and Kear (1960) originally placed the Urawitiki Measures, with the rest of the Rengarenga Group, in the Lower Jurassic. More recently, this has been revised, on the basis of faunal evidence and the Urawitiki Measures is now considered Middle Jurassic in age (Waterhouse and White, 1994). The New Zealand stage equivalent of the Middle Jurassic is the Temaikan. Figure 1.34 summarises the correlation between the New Zealand and International Time Scales between the Upper Triassic and Upper Jurassic. Haq and Van Eysinga (1987) place age constraints on the Temaikan between 176 Ma to definitely 163 Ma, but possibly 154 Ma which approximately correlate with two recently published but differing positions for the Temaikan/Heterian boundary (Westermann, 1996; Stevens, 1997) (Figure 1.34). Correlation of the upper boundary with the International Time Scale has not been accomplished due to the lack of any Upper
### Figure 1.34

Correlation between the New Zealand and the International Time Scale, for stages and series referred to in this thesis. Dashed lines are uncertain boundaries. Differing opinions on the position of the Temaikan/Heterian boundary based on ammonite faunas are plotted (1 = Westermann, 1996; 2 = Stevens, 1997). Correlation based on: Fleming and Kear, 1960; Haq and Van Eysinga, 1987; Westermann, 1996; Stevens, 1997.
Callovian or Oxfordian (Middle Jurassic) guide fossils in New Zealand (Hudson, et al., 1987).

No isotopic dating has been carried out on any of the Murihiku Supergroup sediments in the North Island. However, macrofaunal distribution within the marine formations provides biostratigraphic control (summarised in Figure 1.35). The youngest beds of the Opango Formation, underlying the Urawitiki Measures at Te Maika Peninsula, contain a late Ururoan fauna, including *Dactylioceras* cf. *anguinum* (Reineke) at Ururoa Point (Marwick, 1953) which Spath (1923) dated as Toarcian. Later, Westermann (1996) correlated these faunas with the Lower Toarcian, occurring in the upper (but not uppermost) Ururoan.

The predominantly non-marine Urawitiki Measures contain mainly floral fossils. Hudson (1983) reported finding only an indeterminate bivalve at Rengarenga Point, Te Maika Peninsula. However, no other fauna has been found *in situ* and only trace fossils have been discovered, in addition to terrestrial palynomorphs, along the west coast of Te Maika Peninsula (Enclosure 1). The uppermost ~60 m of the formation contains various fossil macroflora and microflora within fossil-forest-bearing beds. In addition, an abundance of indeterminate compressed and coalified plant material occurs throughout.

The Opapaka Sandstone, immediately overlying the Urawitiki Measures, contains the type Temaikan fauna. Marwick (1953) and Hudson (1983) noted faunas including *Belenopsis mackayi* Stevens (characteristic of lower Temaikan beds in south-east Otago, Speden, 1971), *Meleagrinella* cf. *echinata* W. Smith, *Pleuromyra milleformis*
Figure 1.35 Suggested age constraints for the Rengarenga Group and neighbouring formations exposed in Kawhia Harbour based on faunal evidence. For full faunal lists see Fleming and Kear, 1960. Solid correlation lines and time scale after Haq and Van Eysinga, 1987 (Figure 1.34). Dashed correlation lines derived from biostratigraphic data after Hudson, et al., 1987 / Marwick, 1953; Hudson, 1983, pers. commun., 1998 / Hudson, pers. commun., 1998 / Marwick, 1953 / Spath, 1923.
Marwick and *Hibolithec catlinensis* Hector. The latter two taxa strengthen the correlation with the Temaikan in Southland. *Meleagrinella* ranges in age from late early Temaikan to earliest late Temaikan, but a lack of late Temaikan taxa implies a late early to mid Temaikan age for the Opapaka Sandstone. Temaikan ammonite faunas from marine Jurassic strata in the Murihiku Supergroup suggest a correlation between the mid Temaikan and the Bajocian (Hudson, pers. commun., 1998).

The overlying Wharetanu Measures are non-marine, afualal and similar to the Urawitiki Measures. Based on the late Temaikan to early Heterian Oraka Sandstone (Hudson, et al., 1987), which lies stratigraphically above, the Wharetanu Measures are probably mid-late Temaikan in age. Therefore, a refined age for the Urawitiki Measures, based on current assimilated information from the fauna of stratigraphically proximal formations, is early-mid Temaikan (probably early Bajocian) between 175 and 180 Ma.

**Local Structure**

Dip and dip direction of strata were recorded at several localities within the Urawitiki Measures (Enclosures 1-5). The average dip and dip direction is 39→091° (with dips ranging between 32-48° and dip directions between 070-101°) - almost exactly a north-south strike and parallel to the coastline. There is no systematic change in dip or dip direction throughout the formation, suggesting the slight variation may be due to differential compaction and/or post-depositional folding.
The whole Urawitiki Measures sequence observed is well jointed, often dividing the beds into approximately cubic blocks (Figure 1.36). The joint planes occur in three sets: perpendicular, parallel and oblique to strike (for example, Figure 1.37(a)). Calcite infills were observed in sheltered locations. The orientation of the sets suggests the joints may have formed contemporaneously with the regional folding that occurred during the early Cretaceous (Figure 1.37(b)).

Figure 1.36 Jointing patterns and honeycomb weathering in Urawitiki Measures sandstone, West Coast section, Te Maika Peninsula, Kawhia Harbour. Photo faces down dip. Staff is 1.5 m long.
(a) Equal area stereonet showing joint sets at Locality 20 (Enclosure 1), Urawitiki Point. Sets are: (1) perpendicular, (2) parallel and (3) oblique to bedding strike. Data from all localities recorded in Table D1, Appendix D.

(b) The relationship of joint sets to major folds. Sets are (1) perpendicular, (2) parallel and (3) oblique to fold axes. After Park, 1989.

Figure 1.37 Example of joint sets in the Urawitiki Measures sandstone, West Coast section, Te Maika Peninsula, Kawhia Harbour and their possible relationship to the regional folding.
Only minor faulting was observed in the Urawitiki Measures with dip slip movements of up to 40 cm of very localised extent (for example, Figure 1.38). Three planes were recorded striking approximately south-east to north-east which may be associated with the major north-east striking faults to the north of the harbour (for example, the Oparau Fault, Figure 1.32) and formed concurrently with the regional folding episode.

![Figure 1.38](image)

**Figure 1.38** Minor faulting (arrowed) affecting a conglomerate bed, Urawitiki Measures, West Coast section, Te Maika Peninsula, Kawhia Harbour. Fault planes are arrowed. Staff is 1.5 m long.

*Curio Bay, Southland, South Island*

A second terrestrial sedimentary sequence with exposures of in-growth-position fossil forest floors is investigated at Curio Bay, Southland, South Island (Figure 1.39(a), Figure 1.310). At this locality, virtually flat-lying sandstone, conglomerate and siltstone crop-out on the shore platform and cliffs. Fossilised tree stumps, preserved in growth position (for example, Figure 1.39(b)), and many prostrate fossilised trunks, are
Figure 1.39  (a) Locality map of secondary study site: Curio Bay, Southland, South Island, New Zealand.
(b) Example of an in-growth-position fossilised tree stump at this locality. Diameter = 32 cm. Photo courtesy of W. Cooper, Department of Conservation, Invercargill.
distributed over wide ledges on the shore platform. The present day erosion surface is approximately parallel to the palaeosurface and exhibits the fossilised tree stumps in their original positions on the forest floor. Fossilised tree stumps can also be observed in the cliffs eastwards to Porpoise Bay and scattered fossilised wood was found in similar strata to the west at Slope Point (Figure 1.310). Blue-grey siltstone beds at Curio Bay contain coalified compressions and impressions of foliage, but the material observed by the author was very poorly preserved. In contrast, the fine-grained beds yielded a diverse and well-preserved spore and pollen assemblage.

The fossil-forest-bearing strata at Curio Bay were first described by Hector (1886) and additional information was supplied by Park (1887). Watters, et. al (1968) mapped the sediments as Temaikan in age, but a formal lithostratigraphic subdivision has not been undertaken. Arber (1917) and Edwards (1934) provided a comprehensive description of the fossil macroflora at Curio Bay and two species of *Osmundites* (renamed *Ashicaulis*, refer to Section 4.22) were described from petrifactions by Kidston and Gwynne-Vaughan (1907). General accounts of the sedimentology and fossil flora have been published as part of field trip guides (Guy-Ohlson, 1979; Raine and Pole, 1988) and Pole (1982, 1988, 1990) has provided additional information about the geology and fossil flora since his undergraduate report in 1982. More recently, Pole (1999) has made a significant contribution to the understanding of the palaeoecology of the fossil forest in an investigation of the structure of the fossilised stumps in the fossil forest floor horizons. Use of Pole’s (1999) data for comparison with interpretations from the Kawhia Harbour fossil forest in North Island is made with his permission.
Figure 1.310 The regional geology and locality of Curio Bay and Slope Point on the Southland coast. Teraikan bedrock extends throughout the map area.

Regional Structure and Stratigraphy

Jurassic strata, part of the Murihiku Supergroup, crop-out over approximately 120 km within the north-west/south-east striking axial zone of the Southland Regional Syncline, from Bastion Hill near the Oreti River to False Islet in the east (Figure 1.311) (McKellar
and Speden, in Suggate, 1978). Several double-pitching secondary folds, which rarely
dip >50° (Speden, 1959), form an extensive area of Jurassic outcrop which reaches the
coast in the south and east of the area.

Terrestrial-deltaic and marine Temaikan facies crop-out in the Hokonui Hills and east of
the Mataura River where the plant beds have been described and named the Mataura
Group (Wood, 1956). The undifferentiated Temaikan sediments exposed in the area
between Fortrose, Tokonui and Curio Bay are dominated by terrestrial deposition
(Figure 1.311) (McKellar and Speden, in Suggate, 1978). Further work is required to
resolve the stratigraphic relationships of the strata within this southern region.

Age

Edwards (1934) considered the fossil-flora-bearing strata of Curio Bay to be “probably
not earlier than Middle Jurassic”. The Curio Bay strata are considered Lower Temaikan
in age occurring below fossils of the Haastina haastiana Assemblage Zone (McKellar
and Speden, in Suggate, 1978). Therefore, the suggested age of the Curio Bay strata
implies approximately contemporaneous deposition with the Urawitiki Measures in
Kawhia Harbour. A study in progress on the biostratigraphy of the terrestrial
palynomorph assemblages indicates the Curio Bay horizons may be slightly younger
than those at Kawhia (Raine and de Jersey, pers. commun., 1998).
**Figure 1.311** The distribution of Jurassic strata within the Southland Regional Syncline, South Island, New Zealand. The study site at Curio Bay within Temaikan outcrops is labelled on the south coast. Modified from Suggate, 1978.

*Murihiku Supergroup Geological History*

The Kawhia and Southland Regional Synclines are within the *Murihiku* tectonostratigraphic terrane: one of five late Palaeozoic-early Mesozoic fault-bounded belts of largely volcanogenic strata in New Zealand (Figure 1.312) (Cooper, 1989). The Murihiku terrane extends northward to the west coast Triassic-Jurassic sequence of New Caledonia (Grant-Mackie, 1985a). Overall, these sediments are interpreted to represent a composite arc-trench system, of unknown polarity, developed along the oceanward
Figure 1.312 Principal pre-late Cretaceous terranes of New Zealand, indicating the localities of the study sites within the Murihiku volcanogenic terrane. Modified from Cooper, 1989.
perimeter of Gondwanaland and separated from it by a marginal sea (Mackinnon, 1983). In the late Devonian, sea floor sediments were deformed, metamorphosed and accreted on to the margin of Gondwanaland in the region of proto-New Zealand (Fleming, 1979). The metamorphosed sediments and igneous rocks that were consolidated during this orogeny crop-out along the west coast of South Island and are known as the Western Province (Figure 1.312).

During the Permian, a volcanic arc, built on a strip of Proterozoic basement, formed parallel to the Gondwanaland margin, but was separated from the mainland by a sea (Coombs, et al., 1996). From the Late Triassic, the volcanogenic Murihiku sediments were deposited in either a fore-arc (Mackinnon, 1983; Figure 1.313(a)), intra-arc (Howell, 1980) or back-arc (Coombs, et al., 1996) basin, depending on the interpretation of the subduction polarity. The depositional basin trended north-north-west/south-south-east along the Gondwanaland margin. East of the arc, turbidite sediments were being deposited in a transform-trench setting forming the Torlesse Terrane (Figure 1.313(a)).

During the latest Triassic and early Jurassic (190-200 Ma) the Torlesse terrane collided with the volcanic-arc system causing uplift and gentle folding of the Murihiku sediments above sea level - a precursor to the Rangitata Orogeny (Kingma, 1959). A strike-slip terrane boundary was generated between the Murihiku sediments and the source volcanic arc; the arc later represented by the Brook Street Terrane (Frost and Coombs, 1989). Pulses of plate movement caused short-lived fluctuations in sea level affecting depositional environments along the coastal margin of the Murihiku basin. However,
Figure 1.313 Palaeogeographic reconstructions of the Gondwanaland margin in the proto-New Zealand region. Modified from Mackinnon, 1983.
(a) Reconstruction in late Triassic times showing Torlesse sediments accumulating in trench-transform settings off Gondwanaland, as the volcanogenic terranes, including the Murihiku, form in an island-arc-trench setting to the west.
(b) Reconstruction in the latest Jurassic-early Cretaceous following closing of the marginal sea behind the volcanic arc and collision of the Torlesse sediments roughly parallel to the Gondwanaland margin.
terrestrial sediment deposition in this region ceased in the Upper Jurassic. By the mid-Cretaceous the marginal sea between the Gondwanaland plate and the oceanic plate had closed and all terranes had sutured to the Gondwanaland continent (Figure 1.313(b)) (Coombs, et al., 1996). Today, the sediments that filled the Murihiku basin are geographically divided by the Alpine Fault (Figure 1.312).

**New Zealand Middle Jurassic Palaeolatitude**

Recent southern continent palaeogeographical reconstructions, based on palaeomagnetic data, place New Zealand in high southern palaeolatitudes during the Jurassic (for example, Grunow, et al., 1991; Lawver, et al., 1992; Enay and Cariou, 1997). In addition, discussions on late Jurassic palaeoclimatology use reconstructions which also locate New Zealand very close to the South Pole, even up to 80-85° South (for example, Ross, et al., 1992; Rowley, 1992). However, there are also arguments for New Zealand occupying mid-latitudes during this period based on a single palaeomagnetism study (Grindley, et al., 1980) and palaeobiogeographical evidence (for example, Stevens, 1977, 1980a, 1989; Stevens and Fleming, 1978; Broekhuizen, 1984).

Grindley, et al. (1980) suggested a palaeolatitude for New Zealand of 66° South between the uppermost Triassic and early Jurassic. This interpretation was based on 24 palaeomagnetic samples from the Glenham Porphyry which intrudes Murihiku sediments in Southland. It is the only palaeomagnetic determination for the Murihiku area to date. Further, the suggestion that New Zealand occupied mid-latitudes (~60-70°
South) during the Middle Jurassic is said to account for the apparent southward migration of Tethyan (warm-temperate) faunas around the Gondwanaland coast and the absence of a Palaeoaustral (cool-temperate) fauna in the New Zealand region at this time (Stevens, 1980a, 1985a).

Based on the assumptions listed below, the author considers New Zealand to have occupied high latitudes during the Middle Jurassic.

1) **The Glenham Porphyry palaeomagnetic determinations, placing New Zealand at 66° South during the uppermost Triassic to early Jurassic, are uncertain.**

Oliver (pers. commun., 1997) noted difficulties with magnetic overprints and expressed uncertainty over the final palaeopole determination in the Grindley, et al. (1980) study. Magnetic overprints have also prevented any palaeopole determinations during a recent study of hundreds of Murihiku samples (Grant-Mackie, pers. commun., 1999).

2) **The Murihiku terrane was intrinsically linked to an island arc setting off the south-east coast of Gondwanaland during the Jurassic.**

The depositional setting of the Murihiku sediments within a basin parallel to an island-arc near the Gondwanaland margin (Mackinnon, 1983; Figure 1.313) implies the Murihiku terrane is unlikely to have rafted to its current position from a different setting in lower latitudes. It must also fit into any modelled
reconstruction of the southern continents for the Jurassic (for example, Grunow, et al., 1991; Lawver, et al., 1992). Further, in this palaeogeographical setting, warm Tethyan ocean currents could well have flowed eastwards around the Gondwanaland margin to the proto-New Zealand region in high palaeolatitudes; extending the realm of the warm-temperate Tethyan invertebrate faunas (observed by Stevens, 1980a, 1985a).

3) **Wider, warm climatic belts during the Jurassic extending into the high palaeolatitudes.**

Geological evidence for a globally warmer climate during the Jurassic than today helps explain the occurrence of diverse high palaeolatitude vegetation growth (Figure 1.1) and the extension of the Tethyan faunal realms into high southern palaeolatitudes. Evidence for a warm and humid Jurassic to high palaeolatitudes includes increased coal production worldwide and the shifting of the palaeofloristic and Tethyan/Boreal invertebrate realm boundaries northward during the Bathonian and Callovian (Frakes, et al., 1992). In addition, diverse fossil floras from high Jurassic palaeolatitudes have been found in Patagonia (Calder, 1953) and northern Victoria Land, Antarctica (Jefferson, et al., 1983) (Figure 1.1).

Accepting the evidence for the above assumptions, recent palaeomagnetic data from Thurston Island in the Antarctic constrains the palaeogeography of the southern continents very well for the period between 180 and 173 Ma, the early-mid Jurassic (Grunow, pers. commun., 1996). Samples were collected over as many widely scattered
sites and different cooling units as possible, within any given intrusion, to average out secular variation and define geomagnetic poles for intervals between 230 and 110 Ma (Grunow, et al., 1991). Subsequent palaeogeographic reconstructions, based on these measurements (for 175 Ma, Grunow, et al., 1991) and sea floor magnetic anomalies (for 160 Ma, Lawver, et al., 1992), locate the North and South Islands of New Zealand at similar high palaeolatitudes of 75-78° South in the Middle Jurassic (Figure 1.314).
Figure 1.314 Palaeogeography of the southern continents in the early-mid Jurassic (~175 Ma) to indicate the palaeolatitudinal position of North and South Islands, New Zealand. Modified from Grunow, et al., 1991; Lawver, et al., 1992.
1.33 Antarctica Locality

Allan Hills nunatak, Transantarctic Mountains

At the third collection locality, Weller Coal Measures (Member C) strata of the late early Permian (~265 Ma) Beacon Supergroup, containing abundant fossilised wood (for example, Figure 1.315), crop-out at Allan Hills in the Transantarctic Mountains. The nunatak protrudes from the edge of the East Antarctic Ice Sheet north-west of Ross Island in the Ross Dependency (Figure 1.316).

The fossil flora within the sandstones, siltstones and coals consists dominantly of fossilised wood, transported to the site of burial by an extensive Permian meandering (Francis, et al., 1994) or braided (Ballance, 1977; Cunéo, et al., 1993) river system. Rare fossilised tree stumps, not preserved in growth position, and large fossilised trunks up to 20 m long occur distributed throughout the formation (Francis, et al., 1994; personal observation, 1997). Carbonaceous siltstones contain poorly preserved and highly carbonaceous Glossopteris and Gangamopteris leaves and palynomorph assemblages (Kyle, 1976; Kyle and Schopf, 1982; Francis, et al., 1994).

The fossil wood from Allan Hills has previously been described by Kräusel (in Plumstead, 1962) who named two new species (Taeniopitys scotti Kräusel and Dadoxylon allani Kräusel) from a collection made during the Trans-Antarctic Expedition (1955-1958). The taxonomy of the Allan Hills fossil wood is under review
by Francis (pers. commun., 1997) who has also published an initial study of the growth rings of selected samples (Francis, et al., 1994).

The Transantarctic Mountains occupied a position in the interior of Gondwanaland, on the edge of the East Antarctic craton and in the polar region at least until approximately 200 Ma when the supercontinent began to divide. Smith (unpublished data, in Barrett, 1991) suggested the palaeolatitude of the Allan Hills region in the late Permian was 80-85° South (Figure 1.317), which is similar to its current latitude.

Figure 1.315 Fossilised tree trunk at Allan Hills, Transantarctic Mountains, Antarctica. White clast on trunk = 15 cm wide.
Figure 1.316  Locality map and geology of Allan Hills nunatak within the Transantarctic Mountains, Antarctica. Member C of the Weller Coal Measures, the origin of the fossil wood studied in this thesis, is mapped as Permian strata. Modified from Grapes, et al., 1974.
Figure 1.317 Palaeogeography of pre-breakup Gondwanaland to indicate the palaeolatitudinal position of Allan Hills, Transantarctic Mountains, Antarctica. After Lawver and Scotese, 1987.

1.34 Summary

The comparable ages and palaeolatitudes of the two fossil forest deposits at Kawhia Harbour and Curio Bay within the New Zealand Murihiku Supergroup contain a diverse and well-preserved palaeobotanical record of Temaikan vegetation at polar palaeolatitudes and which well suited to a palaeoecological and palaeoclimatological investigation. The comparable palaeolatitude of the Weller Coal Measures fossilised wood from the Antarctic Permian provides additional material for a study of the affects on vascular plant growth of living in the polar light regime.
1.4 FIELDWORK AND CURATION

1.41 New Zealand Fieldwork

_Kawhia Harbour, Waikato, North Island_

Mapping and Exposure

The coastline from Otoretaitua Point, Te Maika Peninsula, eastwards to the headland west of Totara Point on neighbouring Totara Peninsula was mapped and six stratigraphic sections measured (Figure 1.41). Permission was granted for this fieldwork by the Te Maika Trust board. The sections describe the entire exposed extent of the Urawitiki Measures on Te Maika Peninsula, plus the portion in which fossilised tree stumps are exposed along strike on Totara Peninsula. The stratigraphically lowest section, along the west coast of Te Maika Peninsula, contains no fossilised tree stumps. The upper five sections are along strike from each other and all contain fossilised tree stumps. The coastal exposures from Otoretaitua Point eastwards to Opapaka Point constitute the Type Section of the Urawitiki Measures, described in detail in Appendix C. Table 1.3 lists the localities and grid references of the sections measured.

Recent dune and grass cover prevented mapping inland. However, the coastal exposures were good on the shore-platform and coastal cliffs of both Te Maika and Totara Peninsulas. A stratigraphic gap of approximately 190 m occurs, due to dune and beach
Figure 1.41  Map of Te Maika and Totara Peninsulas, Kawhia Harbour, to show the localities of the stratigraphic sections. Map modified from Waterhouse and White, 1994.
1-6 = stratigraphic sections (names as referred to in the text and grid references in Table 1.4).
sand cover, between the West Coast and the Opapaka Point section, on Te Maika Peninsula (Figure 1.42). There is very poor exposure along strike in Waitapu and Waipapa Bays where bush grows down to high tide level, and the bays are full of estuarine muds and sands. Small exposures, at Onepoto Point, yielded only massive,

Table 1.3 Grid references for the Urawitiki Measures stratigraphic sections, measured on Te Maika and Totara Peninsulas, Kawhia Harbour (based on the New Zealand Topographical Map 1:50 000, NZMS 260, Sheet R15).

<table>
<thead>
<tr>
<th>Enclosure</th>
<th>Section name</th>
<th>Grid references</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>West Coast, Te Maika Peninsula</td>
<td>6505 4375 - 6550 4465</td>
</tr>
<tr>
<td>2</td>
<td>Opapaka Point, Te Maika Peninsula</td>
<td>6575 4460 - 6585 4460</td>
</tr>
<tr>
<td>3</td>
<td>Northern Ohanga Bay, Te Maika Peninsula</td>
<td>6580 4450 - 6590 4450</td>
</tr>
<tr>
<td>4</td>
<td>Southern Ohanga Bay, Te Maika Peninsula</td>
<td>6585 4435 - 6590 4445</td>
</tr>
<tr>
<td>5</td>
<td>Shore platform to the west of the jetty (Jetty), Te Maika Peninsula</td>
<td>6575 4395 - 6590 4405</td>
</tr>
<tr>
<td>6</td>
<td>Totara Peninsula</td>
<td>6570 4195 - 6575 4200</td>
</tr>
</tbody>
</table>

coarse sandstones containing rare, scattered igneous clasts and a narrow conglomerate bed, similar to those observed in the upper portion of the West Coast section (Enclosure 1). Further, shore platform observation was hindered in the Jetty section by prolific intertidal marine life in the sheltered bay. A change in the sedimentological and palaeontological characteristics observed in exposures either side of this stratigraphic gap necessitates separate discussion of the upper and lower parts of the formation (Chapter 2, Sections 2.22 and 2.23).
Figure 1.42  Urawitiki Point, Te Maika Peninsula, Kawhia Harbour, facing north-west. The dunes and beach in the foreground account for a 190 m stratigraphic gap within the Urawitiki Measures.

Sampling

In-growth-position fossil wood sampling, from the uppermost strata of the Urawitiki Measures, was minimised in the interests of geological conservation. Fragments loosened by wave action were preferentially collected. Coring was attempted to sample a fossilised log in the cliff on the west coast of Te Maika Peninsula (Figure 2.25(a)), but was discontinued due to the detrimental effect on the specimen.

*Ex situ* fossilised wood was collected loose from the shore platform on the west coast of Totara Peninsula, in Ohanga Bay and from the Jetty beach on Te Maika Peninsula. Due
to the sheltered nature of the inlet between Te Maika and Totara Peninsulas, it is assumed that these samples had not travelled far from their originating strata and are considered to be derived from the Urawitiki Measures. Fossil leaf collecting was minimal, and proved difficult due to the friable nature of the dominantly siltstone substrate.

*Curio Bay and Slope Point, Southland, South Island*

**Mapping and Exposure**

A stratigraphic section was measured from the shore platform at Curio Bay northeastwards to South Head (G47/1125 8685 to G47/1180 8675; Figure 1.43), mainly from the sea cliff outcrop which is ~6-10 m high and flat-lying (Figure 1.44). The section included three of the fossilised tree stump horizons exposed on the shore platform within Curio Bay. The upper part of the section, seen in the sea cliffs, contained no fossilised stump horizons, but fine-grained beds containing fossilised leaves were observed. Exposure was excellent on the shore platform and good below the intensely weathered sandstones above the splash zone in the sea cliffs (Figure 1.44).

Track-side cuttings on the cliff-top at Slope Point, west of Curio Bay (Figure 1.310), in sandstone of a similar age, composition and texture to that at Curio Bay, yielded exquisitely preserved *ex situ* portions of tree fern rhizomes and well-silicified fragments of fossilised wood (Chapter 4, Section 4.2). No fossil plants were found in-growth-position at this site.
Figure 1.43  Map to show the locality of the stratigraphic section at Curio Bay, Southland. Base map courtesy of W. Cooper, Department of Conservation, Invercargill.
Figure 1.44  The sea cliff at Curio Bay, Southland, looking south-west showing the flat-lying bedding attitude. Figure is 1.82 m tall.

Sampling

Curio Bay Scientific Reserve includes land first designated as a scenic reserve in 1905, but the fossil forest deposit below the high water mark was not protected until 1928. The reserve is managed by the Southland Conservancy section of the New Zealand Department of Conservation. Collection of fossil macroflora from the site was restricted to material found within \textit{ex situ} beach boulders which had been largely collected out by previous visitors to the site. A Department of Conservation Collecting/Research Permit (#9798/144/06/01) issued by the Conservation Officer at the Southland Conservancy in Invercargill was obtained to collect fine-grained lithologies (although sand and gravel is specified on the permit!) for palynomorph analysis from the cliffs at Curio Bay (Appendix A). Sampling at Slope Point was unrestricted, but only loose \textit{ex situ} samples
from track-side cuttings on the cliff-top were collected.

1.42 Antarctica Fieldwork

Allan Hills nunatak, Transantarctic Mountains

Sampling of fossil wood from Allan Hills was undertaken on a joint New Zealand-Swiss expedition during December 1997, funded by the Swiss National Science Foundation. Fossil wood fragments derived from Member C sandstones of the Weller Coal Measures are distributed loosely over the entire Permian exposure (Figure 1.316) but are weathered by wind erosion. Samples collected are rarely larger than 15 cm in their maximum dimension and due to the abundance of specimens there are many still remaining at the site. A stratigraphic section was not measured as the specimens were collected ex situ.

1.43 Curation

All hand specimens, palynomorph slides, Scanning Electron Microscope stubs and lithological and fossil wood thin sections are curated and held in the School of Earth Sciences, Victoria University of Wellington (V.U.W.). Samples are referred to by their V.U.W. collection numbers in this study. Lithological sample numbers are prefixed by 365**, macrofossil samples by VH*** and palynomorph samples by VP***. New Zealand Geological Society Fossil Record File numbers are recorded in Appendix B.
CHAPTER 2
DEPOSITIONAL ENVIRONMENT

2.1 INTRODUCTION

The following chapter presents the results from sedimentological investigations carried out at the two New Zealand Middle Jurassic fossil forest study sites. The steeply-dipping strata (Enclosures 1-5) at Te Maika and Totara Peninsulas within Kawhia Harbour allow a detailed facies analysis from the six stratigraphic sections (Figure 1.41; Table 1.3). A model of the depositional environment for both the lower strata and the uppermost fossil-forest-bearing horizons at this site is then proposed. Less extensive exposure and flat-lying strata at Curio Bay restricted the sedimentological investigation to one stratigraphic section (Figure 1.43), within which the sedimentary structures were poorly preserved and only a broad interpretation of the depositional environment is possible.
2.2 URAWITIKI MEASURES, KAWHIA HARBOUR, WAIKATO, NORTH ISLAND

2.21 Introduction

The sedimentology and palaeontology of the Urawitiki Measures Type Section at Te Maika Peninsula is described and analysed in the following section. All of the West Coast section on Te Maika Peninsula is exposed (Enclosure 1), but only 75% of the Opapaka Point section (Enclosure 2) is exposed due to beach sand cover. Additional information from the other four sections measured along strike, contributes to a facies analysis and facies model. This section concludes with a reconstruction of the evolving depositional environments represented from the base to the top of the formation.

2.22 West Coast Section, Te Maika Peninsula

Summary Section Description

Location:

Otoreaitua Point (R15/6505 4375) northwards along the west coast to Urawitiki Point (R15/6550 4465), Te Maika Peninsula. Previously described by Fleming and Kear, 1960; Kear and Fleming, 1976 and Hudson, 1983.
Stratigraphic Position:
Urawitiki Measures, Rengarenga Group (early-mid Temaikan/Middle Jurassic);
0-285.5 m (from lowermost exposure).

Summary Lithostratigraphic Description:

The measured section is plotted in full (Enclosure 1), presenting field data alongside a
graphic log. A detailed description of the mapped units is tabulated in Appendix C. The
lithologies consist predominantly of sandstone (93%) with minor conglomerate (6%) and
siltstone (1%).

Figure 2.21 presents a summary graphic log. The lowermost 100 m is massive, coarse to
very coarse, densely burrowed sandstone. The sandstone coarsens upwards, containing
lenses of pebbles and siltstone, until an eroded channel base is reached. Above the
matrix-supported pebble lag the unit fines upward to thinly interbedded sandstone and
siltstone overlain by massive coarse to very coarse sandstone. This sequence from the
eroded base is repeated at intervals up section for about 240 m. At this level, a large
channel (~4 m thick at the centre, and greater than 50 m in width) is capped by a dense,
clast-supported conglomerate sheet which is thin (up to 50 cm thick) and laterally
continuous. This is overlain by cycles of coarse sandstone and conglomerate sheets at
narrow intervals, fining briefly to siltstone at 257 m before the next scour and deposition
of a pebble sheet.
Figure 2.21  Summary graphic log of the West Coast section, Te Maika Peninsula, Kawhia Harbour, to show the cyclic sequence of coarse to very coarse sandstone and conglomerate. Details of the section are presented in Appendix C and Enclosure 1.
Concretionary nodules occur throughout and cross-stratification is commonly preserved allowing an interpretation of palaeoflow direction (p. 91). The upper boundary of the section disappears into recent beach sand and dunes.

**Sedimentology**

The main areas of sedimentological investigation are summarised in Table 2.1. A detailed description follows in the next section.

**Table 2.1** Table of contents comprising the sedimentological analysis of the West Coast Section, Te Maika Peninsula, Kawhia Harbour.

<table>
<thead>
<tr>
<th>Lithologies: Sandstone</th>
<th>Field Description and Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Composition and Classification</td>
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<td></td>
<td>Provenance</td>
</tr>
<tr>
<td>Lithologies: Conglomerate</td>
<td>Field Description and Distribution</td>
</tr>
<tr>
<td></td>
<td>Clast Analysis</td>
</tr>
<tr>
<td>Palaeocurrent Analysis</td>
<td></td>
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</tbody>
</table>
Lithologies: Sandstone

Field Description and Distribution

The dominant lithology is a massive, coarse to very coarse, greenish-grey sandstone (Figure 2.22). It is calcite-cemented, extremely hard and on striking emits a sulphurous odour, indicating significant organic matter content. Conglomerate pebble lenses and silica-cemented, spherical to elongate concretions, often with carbonaceous plant material at the core, are also present at several horizons (Figure 2.23(a) and Enclosure 1). The weathered surface exhibits a vesicular honeycomb texture (Figure 2.23(a)), exfoliation planes and bright orange oxidation staining (Figure 2.23(b)).

Figure 2.22 The dominant massive sandstone, West Coast section, Te Maika Peninsula, Kawhia Harbour. Staff = 1.5 m long. Locality 2 (Figure C1, Appendix C), mapped unit WC2 (Appendix C).
Figure 2.23  Features of the dominant massive sandstone, West Coast section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
(a) Vesicular honeycomb weathering and concretions with carbonaceous plant material at the core. Locality 1 (Figure C1, Appendix C), mapped unit WC1 (Appendix C).
(b) Exfoliation weathering and oxidation staining. Locality 4 (Figure C1, Appendix C), mapped unit WC4 (Appendix C).
The lowermost 50 m of the section lacks stratification (Enclosure 1). However, medium-scale, planar cross-stratification is evident above the first conglomerate bed (from ~93 m) with both angular and tangential bases preserved (Figure 2.24(a)). Also, rare granular, horizontal laminations occur in minor siltstones at 50-52 m and centimetre-scale trough cross-bedding is present at ~258 m, accentuated by weathering (Figure 2.24(b) and Enclosure 1).

Light grey, faintly laminated, calcite-cemented siltstone pebbles and boulders occur within the lower 230 m, randomly distributed throughout the massive sandstone beds (Enclosure 1). The size of the clasts increases up section with the largest boulder measuring 54 x 22.5 cm (depth indeterminable due to exposure). The boulders are tabular in shape with rounded corners and edges and contain occasional <1 mm wide calcite veins. Rarely, siltstone pebbles are found in concretion cores.

Carbonaceous plant material is distributed throughout, but often concentrated in narrow, irregular and laterally discontinuous layers, 10-30 cm thick. Coalified branch remnants of indeterminate taxonomy are also present (tens of cm long), increasing in size and abundance up section. One silicified log fragment was discovered (Figure 2.25(a)) and cored (p. 61). However, preservation is poor on thin sectioning (Plate 25, Figures 3,4) and taxonomic classification is not possible.
Figure 2.24  Cross-stratification preserved within the dominant massive sandstone, West Coast section, Te Maika Peninsula, Kawhia Harbour.
(a) Angular and tangentially based planar cross-stratification. Hammer = 40 cm long. Locality 5 (Figure C1, Appendix C), mapped unit WC8 (Appendix C).
(b) Centimetre-scale trough cross-bedding accentuated by weathering. Lens cap = 5.5 cm diameter. Locality 17 (Figure C1, Appendix C), mapped unit WC30 (Appendix C).
Throughout the lower 100 m of the section and before the main phase of conglomerate deposition, trace fossils occur randomly distributed, often locally dense. They consist of unbranched, predominantly flat-lying cylindrical burrows, some oblique-vertical with curved shafts and with dimensions up to 15 cm long and 2 cm diameter. The burrow fill is of fine sand, appears segmented and stands in relief against the substrate (Figure 2.25(b)). These forms are classified as *Teichichnus* sp. from the characteristic concave-up meniscate fill.

Thin beds (≤20 cm) of fine- to medium-grained sandstone interbedded with siltstone occur throughout the section (Figure 2.26; Enclosure 1). These layers are commonly cross-stratified with scoured bases and isolated igneous origin pebbles (for example, mapped unit WC17, Appendix C). Small-scale (up to 6 cm high) load structures are also present. These beds often complete a fining upward cycle following conglomerate deposition, for example, mapped unit WC10 (Appendix C). In addition, diverse and well preserved terrestrial palynomorph assemblages have been derived from several siltstone units (Enclosure 1 and Section 4.24).
Figure 2.25 Fossils within the West Coast section, Te Maika Peninsula, Kawhia Harbour.
(a) Silicified log, prior to coring (sample VH120). Lens cap = 5.5 cm diameter, mapped unit WC2 (Appendix C).
(b) *Teichichnus* sp. burrows (sample VH121). Locality 2 (Figure C1, Appendix C), mapped unit WC2 (Appendix C).
Thinly interbedded sandstone and siltstone, West Coast section, Te Maika Peninsula, Kawhia Harbour. Each staff subdivision = 10 cm. Locality 10 (Figure C1, Appendix C), mapped unit WC13 (Appendix C).

Composition and Classification

The dominant sandstone (sample 36536) is poorly sorted (very fine sand to coarse sand grain sizes) containing sub-rounded to angular lithic fragments. The lithic fragments are predominantly fine-grained volcanic and coarse-grained igneous lithologies. A sub-rounded, fine-grained volcanic lithic fragment is illustrated in Figure 2.27. The matrix is of finer lithic and crystal grains and sparry calcite cement. Crystal grains include quartz, feldspar (plagioclase and potassium feldspar) and minor hornblende, muscovite and biotite laths. Quartz grains occasionally exhibit slight undulose extinction, suggesting slight metamorphic pressures and/or a possible igneous source. Many grains are highly...
altered, contain inclusions and are in the process of replacement by calcite-spar. Opaque iron-oxide accessory minerals are distributed randomly.

Amorphous zeolite minerals are present in minor quantities within the sandstone (not illustrated). Clark (1982) studied the zeolite facies metamorphism of the Murihiku Supergroup in the North Island and found laumontite to be the most commonly occurring zeolite mineral. Zeolites have also been studied in Southland Murihiku rocks, but temperature boundaries have not been defined. It is thought that processes other than temperature and pressure related to burial affect the occurrence of this mineral facies (Boles and Coombs, 1977). However, prehnite, which can form at temperatures as low as 90-130°C, occurs extensively throughout the zeolite facies rocks in Southland. Therefore, it is likely that only low temperature metamorphism has affected the rocks at Kawhia Harbour.

The composition of the Urawitiki Measures sandstone has been estimated by counting 200 grains using Dickinson’s (1985) classification scheme (Table 2.2). When the proportions of constituent quartz, feldspars and lithics are plotted on Folk, et al.’s (1970) ternary diagram, the composition falls into the feldspathic litharenite field (Figure 2.28).
Figure 2.27 Photomicrographs of the dominant massive sandstone (sample 36536), West Coast section, Te Maika Peninsula, Kawhia Harbour. Both figures (a) and (b) illustrate a very fine to coarse sand matrix. Dominant grain types include: quartz (Q), feldspar varieties (F), volcanic lithics (Lv) and hornblende (H) in a sparry calcite cement (C). Scale bar = 0.5 mm. (a) Plane polarised light; (b) Cross polarised light.
Figure 2.28  Folk, et al.'s (1970) primary arenite diagram. Sample 36536 (⊗) is located within the feldspathic litharenite field. Q = quartzose grains, F = feldspar grains, L = unstable lithic fragments.

Table 2.2  Grain composition of sandstone sample 36536. Grain classification after Dickinson, 1985.

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Total Quartzose grains (Qt)</strong></td>
<td>32.0</td>
</tr>
<tr>
<td>Qm (monocrystalline quartz &gt; 0.625 mm)</td>
<td>16.5</td>
</tr>
<tr>
<td>Qp (polycrystalline quartz or chalcedony)</td>
<td>15.5</td>
</tr>
<tr>
<td><strong>B. Total Feldspar grains (F)</strong></td>
<td>27.0</td>
</tr>
<tr>
<td>(including zeolites)</td>
<td></td>
</tr>
<tr>
<td>P (plagioclase)</td>
<td>10.5</td>
</tr>
<tr>
<td>K (potassium feldspar)</td>
<td>1.5</td>
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<tr>
<td>Zeolites (altered feldspars)</td>
<td>15.0</td>
</tr>
<tr>
<td><strong>C. Total Unstable Lithic Fragments (L)</strong></td>
<td>41.0</td>
</tr>
<tr>
<td>(including opaques)</td>
<td></td>
</tr>
<tr>
<td>Lv (volcanic/metavolcanic)</td>
<td>35.0</td>
</tr>
<tr>
<td>Ls (sedimentary/metasedimentary)</td>
<td>2.0</td>
</tr>
<tr>
<td>Opaques (altered lithics)</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Provenance

The high proportion of unstable grains (mainly lithic fragments) in the dominant Urawitiki Measures sandstone indicates a high relief source area with minimal physical and chemical weathering. It is compositionally immature, so was either proximally deposited or rapidly transported and deposited with little reworking.

Dickinson (1985) suggested that the detrital content of sandstones can reflect the different tectonic settings of provenance terranes. Therefore, plotting the composition of sandstone sample 36536 on Dickinson and Suczek’s (1979) ternary diagram of provenance types, a dissected magmatic arc origin is implied (Figure 2.29). This could well comprise an arc massif partially capped by a volcanic cover, but also exposing dissected plutonic and metamorphic rocks. Sandstone sample 36536 correlates with key compositional aspects of derivative sands from this mixed source, including feldspatholithic volcanioclastic sands with high P/K (sample 36536 ~ 1:10) and Lv/Ls (sample 36536 ~ 1:18) ratios (Table 2.2; Dickinson, 1985).

Mackinnon (1980a) recognised a Middle Triassic-Jurassic petrofacies for Murihiku sandstones from a collation of studies on Matai, Caples and Murihiku terrane sandstones (Figure 1.312). Sandstone sample 36536 generally correlates with Mackinnon’s (1980a) results of high P:K and Lv:Ls ratios and a high overall proportion of L compared to Qt and F. However, sample 36536 differs by having a larger Qt:F ratio, perhaps reflecting a higher content of Palaeozoic Western Province derived material. Overall, the
compositional features of the Urawitiki Measures sandstone are consistent with derivation from the Brook Street terrane submature oceanic arc (Mackinnon, 1983).

Figure 2.29  Dickinson and Suczek's (1979) ternary diagram to show the distribution of selected sandstone suites with different types of provenance. Sample 36536 (⊗) is located within the dissected magmatic arc provenance field. Q = quartzose grains, F = feldspar grains, L = unstable lithic fragments.
Lithologies: Conglomerate

Field Description and Distribution

Pebbles first appear within the massive Urawitiki Measures sandstone as a thin, discontinuous band 49 m above the base of the West Coast section, Te Maika Peninsula. The clasts are small (longest axis ($D_l$) $\leq$ 1.6 cm) and matrix-supported. Scoured, channel-shaped bedding contacts occur at the base of predominantly matrix-supported pebble beds with larger clasts ($D_l$ $\leq$ 7.2 cm) from 98-245 m (Enclosure 1; Figure 2.210(a)). The pebble density decreases towards the palaeosurface fining upwards to often cross-stratified coarse to very coarse sandstone. Dimensions of these bed forms reached $>$ 50 m wide (measurement limited by exposure) and $\leq$ 5 m depth, generally increasing in size and frequency up section. The axial trend of the channels was indeterminable due to only two-dimensional exposure.

Above 245 m, the pebble beds have a predominantly clast-supported arrangement (Figure 2.210(b)) with clast sizes similar to the channel-based beds, but with a maximum $D_l$ of 10.8 cm. These upper pebble beds exhibit planar scoured lower bedding contacts instead of channel forms. The beds are tabular in shape, up to $-$0.5 m thick and were observed extending laterally as far as exposure allowed. The upper bedding contacts are sharp against overlying coarse to very coarse sandstone.
Figure 2.210 Examples of conglomerate deposition, West Coast section, Te Maika Peninsula, Kawhia Harbour.

(a) Channel-based, mainly matrix-supported. Hammer = 40 cm long. Locality 6 (Figure C1, Appendix C), mapped unit WC9 (Appendix C).

(b) Tabular, mainly clast-supported. Each staff subdivision = 10 cm. Locality 17 (Figure C1, Appendix C), mapped unit WC31 (Appendix C).
Clast Analysis

To determine the composition of the source terrane, clast lithologies are investigated. These are compared to other regional Murihiku conglomerate deposits to ascertain whether they have a common source and to extrapolate palaeogeographical information for the time of deposition. Size, form and roundness parameters provide an indication of the erosion and sorting processes that occurred prior to deposition and could well indicate distance of transport. Palaeocurrent directions can also be estimated from clast imbrication data which is discussed in combination with sandstone cross-stratification (p. 91).

Ten prominent conglomerate beds from the West Coast section, Te Maika Peninsula, are investigated to characterise the separate deposits and test for trends in clast parameters up section. Each bed, for ease of reference, shall be referred to alphabetically up section (Enclosure 1). The mapped unit synonyms are recorded in Appendix C. For sampling techniques and methods of analysis refer to Appendix D.

Lithological Composition

Overall, the clasts collected are predominantly of igneous origin (91%). Volcanic lithologies are most prevalent (74%) and diverse with lower proportions of hypabyssal (16%) and plutonic (1%) representation. Small amounts of sedimentary (6%) and
metamorphic (3%) clasts are also identified (Figure 2.211 and Tables D2 and D3, Appendix D). There are no significant changes in composition up section.

![Pie chart](image)

**Figure 2.211** Proportions of conglomerate clast lithotypes from the West Coast section, Te Maika Peninsula, Kawhia Harbour.

Bartrum (1936) and Macdonald (1954) investigated the petrography of conglomerate beds around the south coast of Kawhia Harbour, including those within the Temaikan at Ururoa and Urawitiki Points (Figure 2.212). Bartrum (1936) identified plutonic, hypabyssal and volcanic igneous, metamorphic and sedimentary lithologies from a small collection of 28 clasts. Macdonald (1954) found igneous clast lithotypes dominated the samples (92%, of which 15% were plutonic). Minor metamorphic (5%) and sedimentary (3%) proportions were also observed.
From these studies, the igneous component of conglomerate clasts from the Murihiku of Kawhia Harbour is consistently dominant at 91-92% of the sample sets. Furthermore, volcanic lithologies in the Urawitiki Measures sandstone (sample 36536, Table 2.2) constitute 85% of the lithic grains with only 5% of a sedimentary origin. The remaining 10% are represented by opaque minerals and may also be volcanic in part. The composition of all the Murihiku conglomerate pebbles studied is comparable with that of the lithic fragments in the matrix sandstone. Therefore, a common source terrane is implied (p. 82).

Clast Size

To characterise the grain size of the clast component in each of the conglomerate beds, the longest axis ($D_1$) of each pebble collected was measured (Appendix D, Tables D4-
The results indicate that the lowermost bed (sample mean $D_l = 0.91 \text{ cm}$; Appendix D, Table D14) contains pebbles that are significantly smaller, at the 99.9% level, than the conglomerate beds up section. Clasts from bed B upwards are generally larger (sample mean $D_l = 2.19-3.92 \text{ cm}$) and show no significant change in size between successive beds.

Analysis of the statistical distribution of $D_l$ values within each sample (Table D15, Appendix D) found that the majority of the conglomerate beds contain moderately well sorted pebbles, with conglomerates A, B and D showing a well sorted and conglomerate E a very well sorted distribution. The skewness of the distributions varies from strongly coarse to strongly fine, but the majority of the samples are coarsely skewed.

Clast Form

Form is defined in many ways by various authors (discussed in Barrett, 1980), but generally refers to the overall shape of a particle (Sneed and Folk, 1958). Form is independent of roundness and surface texture. Maximum Projection Sphericity (Sneed and Folk, 1958) (Appendix D; Figure D2) values are averaged for each bed and plot predominantly between the compact-bladed and compact-elongate clast form fields (Figure 2.213). In contrast, conglomerate A indicates an elongate form overall. However, at the 95% confidence level, there are no significant changes in form up section.
Figure 2.213  Mean Maximum Projection Sphericity values for each conglomerate bed, within the West Coast section, Te Maika Peninsula, Kawhia Harbour, plotted on Sneed and Folk’s (1958) ternary form diagram. Mean values fall predominantly between the compact-bladed (CB) and compact-elongate (CE) fields (Figure D2, Appendix D).

Clast Roundness

Clast roundness was estimated using Krumbein’s (1941a) visual comparative chart in the field (Figure D3, Appendix D). The mean values for each bed range between 0.51 and 0.77 (Table D14, Appendix D) which reflect the intermediate roundness groups on Krumbein’s chart. There is a very gradual, but 99% significant, increase in clast roundness values up section (Figure 2.214). This trend may reflect an increase in abrasion due to a higher proportion of pebbles in the bed load or a change in transport distance or rapidity of flow.
Figure 2.214 Graph to show the gradual increase in mean pebble roundness through the conglomerate beds up section, West Coast section, Te Maika Peninsula, Kawhia Harbour. Roundness Index after Krumbein, 1941a.

Clast Analysis Summary for the West Coast section, Te Maika Peninsula:

(i) Conglomerate A contains significantly smaller clasts than the pebble beds up section. The pebble samples are well to very well sorted with varying degrees of skewness.

(ii) There is no significant change in Maximum Projection Sphericity up section, so clast form lies predominantly in the compact-bladed to compact-elongate form fields (Sneed and Folk, 1958).

(iii) There is a gradual, but significant increase in clast roundness up section.
Palaeocurrent Analysis

Directional data for palaeoflow during the deposition of the West Coast section, Te Maika Peninsula, are derived from cross-stratification structures observed in the dominant sandstone and conglomerate clast imbrication. Field data are tabulated in Tables D4-D13 and D16, Appendix D.

River deposited pebbles, particularly bladed or elongate forms, tend to orientate themselves differently with respect to the current direction depending on flow velocity (Boggs, 1995). It is assumed that flow was rapid in the channels that deposited the West Coast section conglomerates due to the size of clasts being transported (Appendix D). Therefore, palaeocurrent direction is inferred to have been in the direction parallel to the orientation of the pebbles longest axis (D) (ibid.).

Corrected directional data are plotted on contour diagrams (clast imbrication) and rose diagrams (cross-stratification) and are presented against the stratigraphic column in Figure 2.215. Both indices agree and indicate that the lower Urawitiki Measures palaeocurrent direction followed an approximately consistent flow towards the north or north-east at this locality. However, the current appears to rotate temporarily towards the south-east, during ~40 m of deposition, at and below the level of conglomerates C and D. At the top of the section, imbrication from conglomerates I and J becomes polydirectional and an interpretation of the mean palaeoflow direction is not possible.
Figure 2.215 Palaeocurrent vectors (bedding attitude corrected) derived from pebble imbrication (from each of the conglomerate beds) and sandstone cross-stratification (field localities numbered, Enclosure 1) against the summary graphic log, West Coast section, Te Maika Peninsula. Data tabulated in Appendix B. The pebble Kamb contour plots have a Confidence Interval of 2.0 standard deviations. Both are equal area plots. Mean palaeocurrent vectors for each data set are arrowed, and dotted where uncertain. Plots without arrows indicate an indeterminate palaeoflow direction.
Facies Analysis

The sediments documented along the west coast of Te Maika Peninsula coarsen upward from the fine-grained marine sediments of the underlying Opango Formation. The lower Urawitiki Measures consists predominantly of massive sandstone with an increasing proportion of conglomerate up section, suggestive of a prograding deltaic sequence. The West Coast stratigraphic section (Enclosure 1; summarised in Figure 2.216) is interpreted to comprise five facies in three facies associations, outlined in Table 2.3. Figure 2.216 illustrates the distribution of these facies against the summary graphic log. The following section summarises the sedimentological characteristics of the facies associations including detailed descriptions of each facies, listed in Table 2.4. An interpretation of the mode of deposition of each facies and a model for the depositional setting of the lower Urawitiki Measures is then presented.

Facies Associations

The lowermost 98 m of the West Coast section, Te Maika Peninsula, forms facies association UM1 (Figure 2.216). This association consists of only one facies (facies a, see Table 2.4 for all detailed facies descriptions) which contains massive, coarse to very coarse sandstone with rare siltstone lenses (at 50-52 m) and a single pebble lens (Conglomerate A, Enclosure 1). There is little cross-stratification and rare horizontal, granular lamination occurs within the siltstone. *Teichichnus* sp. bioturbation (Figure 2.25(b)) and streaks of carbonaceous plant material form the biogenic content.
Figure 2.216 Summary graphic log and facies log to show the distribution of facies and facies associations interpreted for the West Coast section, Te Maika Peninsula, Kawhia Harbour.
Table 2.3 Facies associations within the West Coast section, Te Maika Peninsula, Kawhia Harbour. Codes are author’s own (parentheses represent minor proportions).

<table>
<thead>
<tr>
<th>Percentage of section</th>
<th>Facies association</th>
<th>Facies codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 %</td>
<td>UM3</td>
<td>$d, e (c)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interbedded massive, coarse to very coarse sandstone with sheet-like, clast-supported conglomerates. Rare interbedded fine sandstone and siltstone.</td>
</tr>
<tr>
<td>51 %</td>
<td>UM2</td>
<td>$b, c, d$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repeated, commonly truncated, cycles of mainly matrix-supported conglomerate lying on scoured bedding contacts. Grain size fines rapidly upward to massive, coarse to very coarse sandstone and interbedded fine sandstones and siltstones. Rare pebble lenses, scattered igneous pebbles and siltstone boulders. Medium-scale planar cross-stratification.</td>
</tr>
<tr>
<td>34 %</td>
<td>UM1</td>
<td>$a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Massive, coarse to very coarse sandstone with pebble lenses and rare siltstone. Fine sandstone and siltstone clasts, bioturbation.</td>
</tr>
</tbody>
</table>

Facies association UM2 consists of repeated, commonly truncated fining upwards cycles between 98 and 245 m (Figure 2.216). A dominantly matrix-supported conglomerate commonly overlies a scoured bedding contact and rapidly fines upward through coarse to very coarse sandstones (facies $b$). At the top of each cycle, fine sandstones occur interbedded with carbonaceous siltstones (facies $c$). Massive, coarse to very coarse sandstone beds commonly interrupt these fining upwards cycles (facies $d$). Facies $d$ also occurs in the uppermost facies association, from 245 m to the top of the section, alternating with sheet-like, clast-supported conglomerates (facies $e$). Between 256 and 258 m fine sandstones interbed with siltstones (facies $c$). Facies associations UM2 and UM3 are unfossiliferous, but carbonaceous streaks occur in increasing size and abundance up section.
Table 2.4  Descriptions of facies within the West Coast section, Te Maika Peninsula, Kawhia Harbour (in stratigraphic order). Codes are author's own.

<table>
<thead>
<tr>
<th>Facies code</th>
<th>Facies description</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Predominantly clast-supported conglomerate.</td>
</tr>
<tr>
<td></td>
<td>Sheet bed forms (up to 50 cm thick, regular thickness, laterally continuous) with linear scoured bases; sharp upper contact; commonly oxidised.</td>
</tr>
<tr>
<td>d</td>
<td>Coarse to very coarse sandstone, rare siltstone boulders and igneous pebbles.</td>
</tr>
<tr>
<td></td>
<td>Massive bedding; occasional medium-scale planar cross-stratification; carbonaceous streaks, concretions.</td>
</tr>
<tr>
<td>c</td>
<td>Fine sandstone and siltstone, rare igneous pebbles.</td>
</tr>
<tr>
<td></td>
<td>Thinly interbedded (cm-scale); sandstones ± scoured bases, medium-scale planar cross-stratification, load structures; siltstone contains carbonaceous streaks and palynomorph assemblages.</td>
</tr>
<tr>
<td>b</td>
<td>Matrix-supported conglomerate (clast-supported at base), fining upwards to coarse-very coarse sandstone.</td>
</tr>
<tr>
<td></td>
<td>Scoured, channel-shaped basal contact; carbonaceous streaks; medium-scale, planar cross-stratification in the sandstone; concretions.</td>
</tr>
<tr>
<td>a</td>
<td>Coarse to very coarse sandstone with rare siltstone and a pebble lens at 50 m (Conglomerate A, Enclosure 1).</td>
</tr>
<tr>
<td></td>
<td>Massive bedding; medium-scale planar cross-stratification; <em>Teichichnus</em> sp. bioturbation; carbonaceous streaks; concretions.</td>
</tr>
</tbody>
</table>

Facies Interpretations and Depositional Setting

The lithologies, sedimentary structures and succession of facies within the West Coast section are comparable to those of an alluvial fan-delta prograding towards the north to north-east. The sediments could well have been deposited on the subaqueous fan-delta
front (facies association UM1) to relatively high on the midfan braidplain (facies association UM3) (Boggs, 1995; Walker and Cant, 1984). Table 2.5 lists the interpretations of the mode of deposition of each facies.

Table 2.5 Mode of deposition interpretations of all facies (in stratigraphic order) within the West Coast section, Te Maika Peninsula, Kawhia Harbour.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Sheet flood gravel</td>
</tr>
<tr>
<td>d</td>
<td>Sheet flood sand</td>
</tr>
<tr>
<td>c</td>
<td>Abandoned stream flow channel</td>
</tr>
<tr>
<td>b</td>
<td>Stream flow channel</td>
</tr>
<tr>
<td>a</td>
<td>Sheet sand bar</td>
</tr>
</tbody>
</table>

Figure 2.217 illustrates the proposed depositional setting of facies associations UM1, UM2 and UM3. At the onset of Urawitiki Measures deposition distributary mouth bars of alluvial sands containing stream-transported debris (fragmented plant material and silt boulders) amalgamated into a massive sand deposit burrowed by a marine organism producing *Teichichnus* sp. traces, on the upper subaqueous fan-delta slope. Minor siltstones and a pebble lens (Conglomerate A, Enclosure 1) represent periods of low and high flow deposition, respectively, on the distal fan. A lack of sedimentological evidence at the level of the marine/terrestrial transition in the stratigraphic section suggests that deposition may have occurred in a sheltered basin.

Facies associations UM2 and UM3 (Table 2.3) imply the interbedding of sheet flood and stream flow/abandonment facies commonly seen in midfan environments (Boggs, 1995).
Figure 2.2.17 Fan-delta model (of arbitrary scale) indicating the facies distribution within the suggested depositional environment of the lower Urawitiki Measures, West Coast section, Te Maika Peninsula, Kawhia Harbour. Diagram based on Spearing, 1974.
The varying skewness of the pebble size samples (Table D15, Appendix D), probably reflects the different sorting processes during channel and sheet flood deposition. Facies association UM2 could well have been deposited low on the midfan due to the development of flow channels, the dominantly sand-sized sediment deposition and the consistent north to north-east palaeocurrent vectors. The temporary switch in palaeoflow towards the south-east, observed in the sandstone cross-stratification and pebble imbrication between ~128-158 m (Figure 2.215), may have been due to local stream flow diversion caused by channel infill.

High on the midfan in facies association UM3, facies d and e interbed where the topographic gradient was steeper. Channels may have been only weakly developed and the gravel bedload would have been deposited rapidly from relatively unconfined flood waters over much of the upper midfan surface. Flooding could well have been caused by flooding in the source area. This depositional setting is represented by the sheet-like nature of the upper conglomerates (F-J, Enclosure 1) and the more fanning nature of the imbrication vectors (Figure 2.215; Enclosure 1).
2.23 Opapaka Point Section, Te Maika Peninsula

Summary Section Description

Location:

Opapaka Point (R15/6575 4460 to R15/6585 4460), Te Maika Peninsula. Previously described by Fleming and Kear, 1960; Kear and Fleming, 1976 and Hudson, 1983.

Stratigraphic position:

Urawitiki Measures, Rengarenga Group (early-mid Temaikan/Middle Jurassic);
472.9-520 m (from first exposure above the stratigraphic gap at the northern tip of Te Maika Peninsula).

Summary Lithostratigraphic Description:

The stratigraphic section is plotted in full (Enclosure 2) presenting field data alongside a graphic log which represents the upper portion of the Urawitiki Measures Type Section. A detailed description of the mapped units is tabulated in Appendix C.
Figure 2.218 presents a summary graphic log. The Opapaka Point section, like that of the West Coast section, consists predominantly of sandstone (66%), but differs by containing rare intraformational pebbles, a higher proportion of siltstone (7%) and coal (2%). Unseen strata account for approximately 25% of the section. The average dip at this locality (35°09') allows observation of the entire section on the shore platform (Figure 2.219(a)).

The lowermost 7 m consist of cyclic carbonaceous sandstones containing many types of sedimentary structures and very thin coal beds. Fossilised tree stumps are rooted in the coals and protrude up into the overlying sandstone (Figure 2.219(b)). Rare draped laminations are observable over the buried stumps. Abundant carbonaceous root traces radiate down from the coals into the underlying sandstone. Repeated cycles of sandstone and coal are interrupted at intervals by sharp scoured contacts at the base of massive, coarser grained sandstone beds. These massive sandstones contain intraformational pebbles and broken branches, trunks and tree-fern stems.

Above 19 m (Figure 2.218), fine to coarse-grained sandstone beds occur with diverse sedimentary structures and occasional siltstone and pebble lenses. Minor siltstone and coal layers with fossilised tree stumps are interbedded at intervals with massive very coarse sandstone to gravel beds as observed lower in the section.
**Figure 2.218** Summary graphic log of the Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Details of the section are presented in Enclosure 2.
Figure 2.219  Opapaka Point, Te Maika Peninsula, Kawhia Harbour.
(a) Location of the Opapaka Point section. Section measured from exposures of shore platform right to left. Looking south-east towards Totara Peninsula, beds dip east. OP16 and OP39 = mapped units (Appendix C).
(b) Fossilised tree stump (no. 2, horizon OPA1, Enclosure 2) rooted in thin coal bed (mapped unit OP2, Appendix C) and protruding into overlying sandstone (mapped unit OP3, Appendix C). Sticker on hammer = 12 cm long. L = laminations draped over the stump; R₁ = carbonaceous root traces radiating from the stump base; R₂ = carbonaceous root traces from the palaeosurface above.
Siltstone beds become thicker and more prevalent up section, generally interbedded with sandstones, but still periodically truncated by massive, occasionally pebbly, sandstone beds with sharp, scoured contacts. Fossilised leaves are found within many of the siltstones and fossilised tree stump horizons are observable up to ~42 m.

The uppermost bed is a medium grained sandstone containing a marine fauna. This is the Opapaka Sandstone formation. Approximately 2 m of uppermost Urawitiki Measures strata are buried under beach sand beneath this bed and above it, lowermost Wharetanu Measures strata are unseen beneath the water level.

**Sedimentology**

The following section contains a description of the lithologies encountered at Opapaka Point, Te Maika Peninsula. The additional four stratigraphic sections measured along strike on the east coast of Te Maika and west coast of Totara Peninsulas (Figure 1.41, Table 1.3) show similar sedimentary characteristics and are used for illustrative purposes. Table 2.6 summarises the main areas of sedimentological investigation.

**Table 2.6** Table of contents comprising the sedimentological investigation of the Opapaka Point section, Te Maika Peninsula, Kawhia Harbour.

<table>
<thead>
<tr>
<th>Lithologies</th>
<th>Sandstone</th>
<th>Siltstone</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palaeocurrent Analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeontology</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lithologies

Sandstone

Sandstone beds in the upper part of the Urawitiki Measures exposed at and along strike from Opapaka Point (Figure 1.33) are thinner bedded (0.07-5.16 m) than those of the lower part (≤0.60-43.3 m) cropping out on the west coast of Te Maika Peninsula. The bedding contacts are mostly sharp, often scoured, laterally continuous and undulate, perhaps due to compaction (Hudson, 1983) or earthquake tremors prior to lithification. Rip-up clasts of coal are evident at the base of mapped unit OP36 (Appendix C; Enclosure 2).

Grain composition and sorting of the dominant sandstone in the Opapaka Point section is similar to that of the West Coast section sample 36536, so a comparable provenance is assumed. However, the Opapaka Point section sandstone appears light brown in colour, which may reflect a higher organic matter content than the greenish-grey lithology stratigraphically below or a different weathering process on the more sheltered east coast of the peninsula. Grain size varies from fine to very coarse sand with rare gritty laminae and pebbles. Sedimentary structures are particularly well preserved in the coarser beds and both normal and reverse grading is evident.

Sandstone and siltstone pebbles are of intraformational origin and occur in layers with a scoured basal contact (for example, mapped unit OP16, Appendix C; Enclosure 2), in
intra-bed lenses or as isolated clasts. Imbrication measurements were not attempted due to the small size of the pebbles and the likelihood that local eddies influenced their orientation.

Cross-stratification is abundant in the sandstones and represents current-deposited ripples and dunes (≤10 cm high and ≤23 cm long). Angular and tangentially based planar foresets, trough cross-bedding (Figure 2.220) and parallel, horizontal laminations can be seen in many beds. Convolute laminations and de-watering structures are also evident in some beds, for example, mapped unit OP5 and OP7 (Appendix C).

Fragments of carbonaceous plant material are abundant throughout the section, are often concentrated at the upper bedding surface but are rare within calcareous concretions (≤10 cm diameter). In addition, hollows left by roots are occasionally infilled with ferric nodules.

Figure 2.220 Trough cross-bedding and cross-stratification in mapped unit OP28 (Appendix C), Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
Siltstone

Siltstone occurs thinly interbedded with sandstone and increases in abundance up section (Figure 2.221). In addition, rare siltstone lenses occur within sandstone beds and occasionally exhibit parallel, horizontal laminations. Often overlain by thin coal beds (p. 108), the siltstones are rich in carbonaceous material comprising abundant roots and leaf compressions at several horizons (Enclosure 2).

Figure 2.221 Carbonaceous siltstone beds with large lateral roots (arrowed), Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
Coal

Thin coal beds (commonly <10 cm thick) occur throughout the section, overlying both sandstone and siltstone beds and are generally laterally continuous within the limits of the exposure. Fossilised tree stump remains are rooted in these layers, and below them, carbonaceous root traces radiate out into the bed beneath (for example, Figure 2.219(b)). The coals range from soft to very hard with varying proportions of siliceous cement. They can be classified at least sub-bituminous rank due to the homogenisation and compaction of plant matter beyond recognition (Tucker, 1991).

Palaeocurrent Analysis

The abundant cross-stratification in the sandstones of the Opapaka Point section, Te Maika Peninsula, provide data for estimating the mean palaeoflow direction throughout the uppermost Urawitiki Measures (Table D17, Appendix D). Palaeoflow appears variable with neighbouring beds exhibiting directly opposing foreset azimuths (Figure 2.222). However, trough cross-bedding indicates the axis of palaeochannels trend west/east, with planar cross-stratification indicating directions approximately perpendicular. With reference to the mean palaeocurrent vectors of the West Coast section (Figure 2.215), it is probable that the direction of flow was towards the east in the Opapaka Point locality.
Figure 2.222 Palaeocurrent vectors (bedding attitude corrected) derived from sandstone cross-stratification and elongate carbonaceous wood fragments (labelled by mapped units, Enclosure 2) against the summary graphic log, Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Data tabulated in Table D17, Appendix D. All plots are equal area. Mean palaeocurrent vectors for each cross-stratification data set are arrowed (double headed arrows = trough cross-bedding).
Widely variable orientations of the long axes of carbonaceous branch and trunk fragments (Table D18, Appendix D; Figure 2.222) negates the use of fossil wood for palaeocurrent analysis. Even a large tree trunk, complete with root ball (Figure 2.223), showed no evidence of attachment to a palaeosurface and may equally have been lodged parallel or oblique to the dominant flow direction.

**Figure 2.223** Fossilised tree trunk, complete with root ball (tap root arrowed), Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Trunk aligned north/south. The lack of palaeosol around the roots and its location in the centre of a massive sandstone bed (mapped unit OP16, Appendix C) suggests it is not preserved embedded in a palaeosurface. Therefore, it cannot be used as a reliable palaeocurrent indicator. Hammer = 40 cm long.
Palaeontology

Fauna

The strata of the uppermost Urawitiki Measures are afaunal. Small (up to 9 mm valve diameter), ribbed bivalve moulds and casts were found with an indeterminate small, silicified stem or branch fragment (18 mm diameter) in sample VH251 (Figure 2.224). This specimen was collected ex situ from the locality of the Totara Peninsula stratigraphic section (Enclosure 3) and is likely to have been sourced from the Opapaka Sandstone formation immediately overlying the Urawitiki Measures. Preservation of the bivalve moulds and casts is poor, however, they resemble *Meleagrinella* which occur in Temaikan shallow marine faunas (Grant-Mackie, pers. commun., 1999).

Figure 2.224 Outline drawing of bivalve moulds and casts found with a fragment of silicified stem or branch (sample VH251), Totara Peninsula section, Kawhia Harbour. Scale bar = 2 cm.
Flora

An abundant and diverse fossil flora is present throughout the Opapaka Point section and along strike to Totara Peninsula in sandstone and siltstone lithologies. Many types of fossil plant organs from several different taxonomic groups are preserved: spores and pollen, seeds, seed cones, twigs, branches, leaves, trunks and stumps.

Preservation

The fossil plants occur in varied states of preservation and many are well enough preserved for taxonomic classification. The specimens have been affected by thermal maturation which begins when non-mineralised tissue softens, collapses and consolidates in an anoxic environment (Schopf, 1975). On accumulation of plant organic matter in sediment and increasing burial depth and temperature the remains eventually become coal. Increasing coalification causes the cellular structure to homogenise and information about the original plant is lost. The mode of preservation of each type of fossil plant material (for example, sporopollenin (spore and pollen), soft tissue (leaves) and vascular tissue (wood)) is discussed with the systematic descriptions in Section 4.2.
Fossilised Tree Stumps

The fossilised stumps are preserved as mounds protruding several centimetres from the palaeosurface (for example, Figure 2.225), or hollows where the wood has not preserved and holes descend into the underlying bed representing the former root system (for example, Figure 2.226). One fossilised standing tree was observed with its trunk protruding through several overlying beds (Figure 2.227). Rarely, badly preserved fossil stumps are represented by a carbonaceous ring on the upper bedding surface. This is the remains of a hollow tree (dead on burial) which had been filled with sand before lithification. Coalified shrub-sized stems (<8 cm diameter) are also present in isolation or as a group surrounding a large fossilised stump. Due to these varying styles of preservation, it is possible to recognise the presence of a fossilised tree stump and at which level it was rooted, even if the stump itself is no longer present. This is very important when measuring stump spacing and discussing forest density and productivity (Section 1.22).

Many of the coalified roots seen radiating outwards and downwards from fossil stump bases are large (up to ~5 cm diameter) and can be traced up to ~2 m laterally (for example, Figure 2.228). Dense networks of finer (<1 cm diameter) roots can be seen throughout the palaeosols. Straight root margins suggest minimal compaction on burial.
Figure 2.225 A mound of fossil wood protruding several centimetres from the palaeosurface to show a type of preservation of in-growth-position fossil tree stumps (no. 45, horizon OPE, Enclosure 2). Large roots can be seen radiating from the base. Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
Figure 2.226 The hollow mould of a tree stump to show a type of preservation of in-growth-position fossil tree stumps (no. 77, horizon SOA2, Enclosure 4), Southern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. Width at top of hollow ~30 cm.
Figure 2.227 Standing tree with large downward penetrating roots (arrowed) to show a root system at the base of an in-growth-position fossilised tree stump (no. 63, horizon NOAI, Enclosure 3), Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
Figure 2.228 In-growth-position fossil stump with extensive root system radiating downwards and laterally from the stump base (arrowed; no. 227, horizon TC3, Enclosure 3), Totara Peninsula section, Kawhia Harbour. Card = 8 cm long.

Fossil Forest Floors

Fossilised stumps occur in successive horizons throughout the uppermost Urawitiki Measures strata in all five sections along strike from Opapaka Point (Enclosures 2-5). Fossilised shrub or sapling stumps (<8 cm diameter; Section 1.22), tree-fern stem fragments and seed cones are also found associated with the fossil tree stump horizons. Fossil leaves are found in fine-grained beds commonly overlying the rooting horizon.
In total, 236 fossilised stumps were recorded throughout the sections measured (Tables H1-H5, Appendix H). Each horizon of rooted fossilised stumps is recognised as a distinct fossil forest floor. Distinctive massive sandstones aid a broad visual correlation between stump horizons in the separate stratigraphic sections. Therefore, the forest cover could well have extended over at least 4 km of the land in Kawhia Harbour from Opapaka Point, Te Maika Peninsula to Totara Peninsula during the early-mid Temaikan (Enclosure 6).

Most of the fossilised stumps observed were recorded in section at the current erosion surface which represents a random line through the original forest floor. Therefore, the spacing of stumps exposed along this line cannot be used to estimate forest density. However, a two-dimensional bedding plane exposure in the Southern Ohanga Bay section on a low sea cliff face was suitable for this purpose allowing observation of the fossil forest floor in plan over an area of 102 m². An investigation into the structure of the fossil forest at this locality is discussed in Section 4.44.

Facies Analysis

The dominance of sheet sandstones, minor channel deposits and the subordinate proportion of fine-grained sediments in the uppermost Urawitiki Measures suggests a facies association representative of a sandy braided river. The Opapaka Point stratigraphic section is interpreted to comprise one facies association of three individual facies, outlined in Table 2.7. Each facies occurs in all sections along strike from
Opapaka Point. Broad correlations can be made between the stratigraphic sections despite poor lateral continuity of individual facies (Enclosure 6). The Opapaka Sandstone Formation directly overlying the Urawitiki Measures is recorded in the graphic logs of the Opapaka Point and Jetty sections from Te Maika Peninsula (Enclosures 2 and 5). This formation is interpreted as being deposited during a shallow marine incursion (Fleming and Kear, 1960; Waterhouse and White, 1994). Figure 2.229 illustrates the distribution of interpreted facies against the summary graphic log of the Opapaka Point section, Te Maika Peninsula.

The following section summarises the characteristics of the facies association with detailed descriptions of each facies. An interpretation of the mode of deposition of each facies and a model for the depositional setting of the uppermost Urawitiki Measures is then presented. Based on the facies analysis, a mechanism of forest floor burial and preservation is suggested and additional palaeoenvironmental information is interpreted from a classification of the palaeosols (rooted horizons, Figure 2.229).

Table 2.7 The facies association of the Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Codes are author’s own.

<table>
<thead>
<tr>
<th>Percentage of section</th>
<th>Facies association</th>
<th>Facies</th>
<th>Summary description</th>
</tr>
</thead>
<tbody>
<tr>
<td>73% (27% unseen)</td>
<td>UM4</td>
<td>f, g, h</td>
<td>Interbedded fine- to very coarse-grained sandstone with siltstone and coal. Rare siltstone clasts and intraformational pebble layers. Abundant medium-scale cross-stratification, including trough cross-bedding. Horizontal and convolute lamination; de-watering structures. Abundant carbonaceous rootlets and fossilised stump horizons.</td>
</tr>
</tbody>
</table>
Figure 2.229 Summary graphic log and facies log to show the distribution of facies and the facies association identified within the Opapaka Point section, Te Maika Peninsula, Kawhia Harbour.
Facies Association UM4

The sedimentological characteristics of facies association UM4 (detailed in Table 2.8) is completely different to facies association UM3 lying between ~231 and 190 m stratigraphically below in the uppermost strata of the West Coast section. During the ~190 m stratigraphic gap and since the deposition of facies association UM3 on the upper midfan slope, the palaeosurface stabilised sufficiently for the establishment of mature trees suggesting that the overall depositional setting changed.

Facies Interpretations and Depositional Setting

The lithologies, sedimentary structures and succession of facies within the Opapaka Point section are comparable to those of a sandy braided river flowing towards the east affected by regular floods of high discharge (Boggs, 1995; Walker and Cant, 1984). Table 2.9 lists the interpretations of the mode of deposition of each facies.

Figure 2.230 illustrates the proposed depositional setting of facies association UM4. The lowermost strata within the Opapaka Point section, Te Maika Peninsula, consist of beds assigned to facies f and include sandstone beds with planar cross-stratification.
Table 2.8  Descriptions of facies within the Opapaka Point section, Te Maika Peninsula, Kawhia Harbour (in stratigraphic order). Codes are author’s own.

<table>
<thead>
<tr>
<th>Facies code</th>
<th>Facies description</th>
<th>Lithologies</th>
<th>Sedimentary structures and biogenic content</th>
</tr>
</thead>
<tbody>
<tr>
<td>h (9% of seen strata)</td>
<td>Medium-grained sandstone to gravel, rare siltstone and pebble lenses. Coal commonly laminates upper surface.</td>
<td></td>
<td>Trough cross-bedding; curved, planar and sinusoidal, medium-scale cross-stratification; rare convolute laminations; rare ferric nodules and calcite veining. Fossilised tree stumps rooted in coal layers with carbonaceous root traces radiating laterally and downwards.</td>
</tr>
<tr>
<td>g (28%)</td>
<td>Medium-grained sandstone to gravel. Intraformational pebble layers; rare siltstone or sandstone pebbles.</td>
<td></td>
<td>Massive bedding with sharp upper and lower contacts. Both normal and reverse grain-size grading. Planar and sinusoidal, medium-scale cross-stratification; convolute and horizontal, parallel laminations; de-watering structures; concretions; coal rip-up clasts; ferric nodules. Carbonaceous branch, trunk and tree-fern stem fragments throughout with fossil stumps commonly rooting from the upper surface.</td>
</tr>
<tr>
<td>f (36%)</td>
<td>Fine- to very coarse-grained sandstone interbedded with thin siltstone and coal. Rare siltstone pebbles.</td>
<td></td>
<td>Commonly fines upward; lower contact generally sharp, upper contact may grade into siltstone or thin (up to 27 cm thick) coal. Planar and curved, medium-scale cross-stratification; rare convolute laminations; de-watering structures; ferric nodules; calcite veining. Fossilised stumps root from the coal with carbonaceous root traces radiating laterally and downwards. Sandstones: carbonaceous seed cones, seeds, branch debris. Siltstones: horizontal, parallel laminations, fossil leaves.</td>
</tr>
</tbody>
</table>
**Figure 2.230** Local depositional environment reconstruction for the uppermost Urawitiki Measures. Based on facies interpreted from the Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. The model shows part of a sandy braided river system, possibly flowing over a shallow sloping braidplain with a high volcaniclastic sediment input from the source mountains maintaining the braided flow. Top right figure after Nemic and Steel, 1988.
Table 2.9  Mode of deposition interpretations of facies (in stratigraphic order) within facies association UM4, Opapaka Point section, Te Maika Peninsula, Kawhia Harbour.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Facies interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>Channel fill and migration</td>
</tr>
<tr>
<td>$g$</td>
<td>Major Sheet flood</td>
</tr>
<tr>
<td>$f$</td>
<td>Vegetated sub-aerial bar top</td>
</tr>
</tbody>
</table>

The orientation of these sedimentary structures (Figure 2.222) suggests the accumulation of large and cohesive bedforms, possibly transverse and lateral bars, between weakly developed braiding channels. Transverse bars are particularly characteristic of sandy braided streams and form as large dunes under high flood conditions (Boggs, 1995). Large lateral bars also develop along the channel sides in areas of relatively low energy subsequent to flooding and aggrade showing planar cross-stratification at an angle to flow. The orientation and type of cross-stratification observed within beds of this facies are consistent with the development of both bar forms. Horizontal, parallel laminations are also evident in the sandstones of facies $f$ indicating deposition from very low energy flows in waning flood currents.

During normal river discharge, vegetation colonised the surfaces of large and established bars, represented by facies $f$, from the water’s edge up to higher and drier areas where primitive palaeosols developed (Figure 2.230). The siltstones could well have been deposited in bar top pools from the settling of fines in trapped flood waters. Horizontal, parallel laminations in these fine-grained beds indicate very low energy depositional conditions. Ferns and bog plants colonised the damp pool edges dropping fronds and
stems into the still water. Anaerobic conditions virtually halted microbial decomposition allowing preservation.

At intervals above ~6 m (Figure 2.229) facies g occurs consisting of massive sandstone beds with abundant carbonaceous branch and trunk debris. Despite the rare occurrence, this facies accounts for a high proportion of the sediment in the section (Table 2.8). The sands of this facies could well have been deposited during floods of particularly high discharge when sediment-laden water inundated the entire river system and deposited a thick sheet of sand over a wide area possibly due to seasonal melt in the source area (Figure 2.230). Sedimentary structures (upper flow regime horizontal, parallel laminations, cross-stratification and de-watering structures) indicate deposition was rapid from a uni-directional flow. Plant debris caught up in the flood was incorporated into the sediment and subsequently preserved. Following flood water drainage, vegetation re-colonised the upper surface and soils began to form.

The sandstones of facies h occur between 18.5 and 26.5 m and exhibit trough cross-bedding and scattered intra-formational pebbles over a scoured lower bedding contact. These sedimentary features are characteristic of channel lag deposits and represent sediment infill of poorly developed channels following their diversion over or through bars during periods of high discharge. The new surface of the infilled channels was colonised by vegetation including trees and primitive soil horizons developed. The consistency of the trough cross-bedding attitudes indicate flow was generally of low sinuosity and in a west/east direction (Figure 2.222).
The sandy braided river depositional setting is characteristic of regions on a relatively steep gradient with an abundant and high rate of sand-grade sediment supply. Fluctuations in water discharge are typically high and rapid and channel banks are easily erodible and generally non-cohesive (Cant, 1982). However, due to the evidence for the accumulation of large bars with mature trees established on their subaerial surfaces it is probable that the river system of the uppermost Urawitiki Measures flowed over a braidplain with a relatively gentle slope. Further, the discharge, although relatively high, probably varied little over long periods. These depositional characteristics interpreted from the uppermost Urawitiki Measures are in contrast to the sandy braided river model of Cant (1982). For example, the gentle palaeoslope proposed may have been the surface of fluvially extended, merging fan toes of prograding fans as interpreted for the West Coast section depositional environment (Figure 2.230). This suggests that, despite the major floods when discharge was very high (facies g), the majority of stream flow was of a much lower discharge and generally insufficient to cause substantial and frequent shifting of large bars and channel forms. The braided nature of the stream flow, interpreted from the low sinuosity of the cross-stratification vectors, could well have been maintained by a high rate of sediment supply from the source mountains.

Forest Floor Burial and Preservation

Fossilised stumps occur within all facies. This reflects the rapid colonisation of all stable surfaces in this depositional setting, including bar tops and abandoned channels. In an actively braiding environment, channel fill and migration facies interleave with bar
deposits as the flow is diverted around rapidly deposited sediment. Therefore, trees growing in these locations would eventually become inundated by migrating channels and their bases buried in saturated sediment as the channel fills and changes course again.

Periods of sudden high discharge during floods would cause this process to speed up. Rapid channel migration and sediment supply would cause increased deposition on the bars, perhaps resulting in burial of tree bases. Rare major floods would have had sufficient energy to fell trees (for example, Figure 2.223) but, more frequently, the discharges were lower. As a result, most of the trees remained upright and their bases were buried in saturated sediment on the waning current (Figure 2.231). Although individual trees may have survived the actual flood intact, they may have died later due to prolonged waterlogging of their root bases while the water table was still high. Flooding of the soil reduces the availability of soil oxygen and inhibits root respiration. This results in decreased root growth and absorption of water and mineral nutrients and affects the production of hormones, eventually causing the death of the plant (Kozlowski, et al., 1991). The lack of aerial roots\(^1\) or buttressing\(^2\) and the presence of

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1 Aerial roots, for example, bald cypress (*Taxodium distichum*) 'knees', grow upward from a submerged tree base so oxygen can diffuse directly from the air into the roots.

2 Lateral roots which grow perpendicularly from the stem in shallow, often peaty and waterlogged soils. The top root surface grows upward to form woody struts which support the tree in an upright position.
Normal river flow conditions. Water table beneath channel beds.

Flood covers landscape up to the base of tree trunks.

Tree dies due to prolonged waterlogging of roots. Flood begins to wane and sheet sand deposited.

Flood waters slowly draining. Dead crown and upper trunk fall and rot away. Trunk base and stump infiltrated by silica-rich groundwater - decomposition halted.

Flood waters drain away completely. Water table drops. Silica precipitates out of disappearing groundwater into wood cells. New surface re-colonised and old stump preserved.

**Figure 2.231** Cartoon diagrams indicating the sequence of events involved in the burial and preservation of the majority of the uppermost Urawitiki Measures trees, Te Maika and Totara Peninsulas, Kawhia Harbour.
deeply penetrating tap roots\(^1\) (for example, Figure 2.227 and Figure 2.228) indicates the preference of the trees in this locality for the usually well-drained sandy soils.

If the tree died as a result of the flood, the portion of the tree trunk and crown above the level of the flood deposit could well have broken off or rotted away. However, the waterlogged sediment causing anaerobic conditions surrounding the stump and trunk-base would have essentially halted decomposition of the organic matter. If drainage had been slow, complete infiltration of silica-rich groundwater into the cell walls and interstices, in addition to the presence of organic compounds derived from the plant matter, would provide the conditions necessary for preservation by cellular permineralisation\(^2\). Once the sediment had dried out and consolidated, renewed vegetation colonisation would occur on the now slightly raised surface. In this way, successive forest floors would have been buried and preserved by consecutive flood events resulting in the sequence of in-growth-position fossilised stump horizons exposed in the current shore platform.

**Palaeosols**

The development of palaeosols on the subaerial portions of the river bars may have consolidated the sandy substrate sufficiently to allow the establishment of trees. However, the frequency of high flood discharges in the region curtailed the development

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\(^1\) Tap roots are prominent main roots which grow downwards and bear smaller lateral roots. In a dry season, these would enable the plant to reach the low water table beneath the dry upper soil layers.

\(^2\) For a detailed discussion on the mode of fossil wood preservation, refer to p. 192.
of soil horizons and only poorly developed profiles are evident throughout the section.

The palaeosols recognised are entire and occur in facies f and h.

The palaeosol profiles observed are classified using a descriptive field nomenclature for separate horizons developed by Guthrie and Witty (1982). In modern soils, each horizon is assessed by noting its position within the soil (above or below other recognised horizons), its lithologic and organic content and its colour. The horizon is then assigned a standard letter or code to fit the characteristics observed. The most commonly occurring palaeosol in the Opapaka Point section consists of a lowermost A horizon of flood deposited sandstones, which has often retained sedimentary structures (Figure 2.232). It contains carbonaceous root traces concentrated in the upper 10-20 cm and often radiating from fossilised stump bases. Therefore, it is comprised of a mixture of organic and mineral matter. The accumulation of organic materials, evident as the thin coal layer on the upper surface, is referred to as the O horizon. The lateral continuity of these layers, within the limits of the exposure, suggest an evenly distributed supply of organic matter, perhaps from a closed canopy overhead. Primitive soils known as Entisols or Spodosols fit this description and can form in 10-100 years (Retallack, 1990). Overlying the coal and often exhibiting draped laminations over the stump, is a further flood sandstone, which covers the tree bases and the forest floor. Development of these profiles is particularly evident in the lowermost 6 m of the Opapaka Point section, Te Maika Peninsula (Enclosure 2).
A further type of palaeosol occurs within the siltstone beds. A dense network of vertical and scattered carbonaceous root traces, perhaps from ferns growing at the edges of bar top pools, occurs throughout the bed with no overlying coal layer and only rare rooted in-growth-position fossilised tree stumps (Figure 2.233). The abundant, small surficial roots would have been active in the upper soil layers during the wet season. Horizon development had not occurred prior to burial in these palaeosols, so Guthrie and Witty's (1982) descriptive nomenclature cannot be applied. However, these deposits can be broadly termed *fluvial* palaeosols, primarily consisting of alluvial sediments (Retallack, 1990).

*Figure 2.232* Repeated Entisol or Spodosol horizons with a fossilised tree stump rooted at one palaeosurface (stump no. 2, horizon OPA1, Enclosure 2), Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
Figure 2.233  Fluvent palaeosol horizons with fine roots descending from the upper surface (arrowed). Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. Hammer = 40 cm long.
2.24 Summary

Depositional Environment

The Urawitiki Measures exposed at Te Maika and Totara Peninsulas in Kawhia Harbour is interpreted to represent two distinct depositional environments during the early-mid Temaikan. The lowermost 285.5 m characterises a river-dominated fan-delta lobe actively prograding in a north to north-easterly direction from the coastal margin of Gondwanaland. Facies associations are interpreted to represent sediments deposited on the subaqueous fan-delta front which coarsen-upward to a subaerial alluvial mid-fan environment. Separated by an 190 m stratigraphic gap, the uppermost 47 m of strata, containing abundant fossil flora and palaeosols are interpreted as facies within a sandy braided river environment, probably developed on the subaerial fan-delta plain. An easterly palaeoflow derived from conglomerate imbrication reflects the overall palaeoslope from which a northerly fan-delta lobe had prograded during deposition of the lower strata in the sequence.

The source area for the entire Urawitiki Measures formation was a volcanically active, high relief, dissected oceanic arc approaching the coastal margin of Gondwanaland to the west of the present day coastline. Channel and scour-based conglomerate beds within the midfan facies of the lower Urawitiki Measures strata and stratigraphically separate
horizons of fossilised in-growth-position tree stumps and palaeosols in the uppermost strata suggest the occurrence of major floods at least every 100-150 years.

Two features of the Urawitiki Measures sedimentary sequence at Te Maika Peninsula require further explanation: the lack of a beach deposit reflecting the transition from marine to terrestrial conditions and the unusual preservation of thick flood deposits in an actively braiding, and therefore erosive, depositional environment. Firstly, Hudson (1983) discussed progradation into a sheltered basin as an explanation for the lack of a recognisable beach deposit and Ballance (1988), referring to similar terrestrial facies in the Puaroa Huriwai Group (Upper Jurassic) at Port Waikato ~70 km north of Kawhia Harbour, suggested that wave-action had been dampened by seasonal floating ice at a high palaeolatitude¹. In the lower Urawitiki Measures strata, rare calcareous siltstone clasts are found within the subaqueous fan-delta sediments. It is more likely that they are the result of upstream erosion of previously deposited and uplifted basinal sediments, or clasts dropped from floating tree stumps or root balls, than possible drop-stones from ice. From studies on modern deltas with similar features (no beach deposit and a low quantity of cross-bedding) (Nemic and Steel, 1988) it is likely that the Urawitiki Measures fan-delta prograded into a relatively shallow basin over a gentle slope with the gradual transition from marine to subaerial conditions not recorded in the geological record.

¹ A palaeolatitude of 66° South was derived from palaeomagnetic data from the late Triassic-early Jurassic Glenham Porphyry intruded into Southland Murihiku sediments (Grindley, et al., 1980). This controversial estimate is ~10° further north than the more recent Grunow, et al. (1991) and Lawver, et al. (1992) reconstructions (p. 49).
Further evidence for a gentle slope or a generally flat-lying topography is the symmetry and lack of reaction wood\(^1\) in the fossilised tree stumps, suggesting that the trees did not grow on steep slopes.

Secondly, the preservation of the products of convulsive events\(^2\) in the geological record, for example, the major floods represented in the uppermost Urawitiki Measures, is rare above base level (Dott, 1983). In addition, the sediment characteristics, deposited virtually instantaneously during a flood event, are likely to be altered significantly if they linger in such an active river environment. Dott (1983) considers the only way to preserve such deposits is for subsidence to carry them below the erosional base level. The Urawitiki Measures base level could well have coincided with sea level, due to the proximity of the depositional environment to the basin margin. Therefore, in order for successive flood deposits to be preserved, sea level must have been gradually rising in relation to the land, at a rate comparable to sedimentation.

Evidence for a high and rising sea level can be found in the process of tree stump preservation at each horizon (Figure 2.231). Prolonged periods of waterlogging are required to allow adequate impregnation of the wood by silica-saturated groundwater, which suggests delayed drainage of flood waters, perhaps due to an already high local water table. The diversity and abundance of the fossil flora (Section 4.2) also suggests

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\(^1\) Reaction wood can be produced by woody plants as the result of a geotrophic physiological response to a sloping substrate in order to maintain a vertical stem.

\(^2\) A "convulsive event" is defined as an extraordinarily energetic event of regional influence (Clifton, 1988).
vegetation growth was not limited by a poor groundwater supply. Further, the local water table must have been high enough to maintain bar-top pools on a predominantly sandy substrate and preserve thin coal beds. Finally, the increasing proportion of siltstone lithologies in the Urawitiki Measures strata (Enclosure 2) could well indicate a general reduction in coarse sediment supply in reaction to a decreasing erosion rate upstream, perhaps caused by a slow relative rise in sea level.

The Opapaka Sandstone, a shallow marine sandstone overlying the Urawitiki Measures, could well reflect the culmination of a gradual rise in relative sea level which eventually caused a marine transgression over the fan-delta. Therefore, the preservation of successive flood deposits within the uppermost Urawitiki Measures could well be due to land subsidence at the basin margin causing a gradual rise in relative sea level and the maintenance of a high base level.

**Sedimentological Evidence for Palaeoclimate**

Features of the sedimentary record, especially within the uppermost Urawitiki Measures, provide indirect evidence of the prevailing climatic conditions, particularly the water regime, at the time of deposition. Evidence for a climate in this region with a high annual rainfall is abundant. For example, the many forms of current-deposited cross-stratification indicate a relatively fast-flowing river fed by frequent rainfall in the source mountains and regular floods. In addition, the preservation of fallen leaves in silts at the bottom of bar-top pools would require permanent stationary water continually being
replenished by rain or groundwater. A lack of desiccation cracks in the siltstones suggests the pools may have been persistent throughout the year.

The presence of deeply penetrating tap roots within the palaeosols imply that a short dry season may have occurred despite the prevailing humid conditions. Further, the preservation of laterally continuous thin coal layers suggests leaf litter that reached the ground accumulated on a moist forest floor. The upper layers dried out in the dry season, leaving only a thin bed to be preserved in the geological record. The lack of evaporite deposits suggest that at no time during the year were temperatures high enough or humidity low enough to evaporate the surface water and soil moisture completely.

2.3 UNDIFFERENTIATED TEMAIKAN SEDIMENTS, CURIO BAY, SOUTHLAND, SOUTH ISLAND

Summary Section Description

Figure 2.31 presents the stratigraphic section measured at Curio Bay on the Southland coast (Figure 1.310) and includes information about the sedimentary structures and fossil flora. The section consists of volcaniclastic sandstone (85%), carbonaceous siltstone (11%) and coal (4%) lithologies. Bedding is flat-lying (Figure 1.44). The lowermost 8 m of the section consists of alternating, relatively thinly bedded (7-195 cm
Figure 2.31  Graphic log of the Curio Bay section, Southland. The stratigraphic location of the palynomorph samples are indicated by their sample numbers (VP***)
thick), dark brown, fine- and medium-grained sandstones with dark blue-grey, carbonaceous siltstones (6-41 cm thick). Three successive horizons of in-growth-position fossilised tree stumps occur rooted in dark brown, fine- to medium-grained sandstones within the lowermost 0.5 m of the section. The long axes of prostrate fossilised tree trunks within the same horizons are oriented predominantly north-west/south-east (Figure 2.32). Several beds within the lowermost 5 m also contain fragments of carbonaceous wood and one carbonaceous portion of a tree fern rhizome (Figure 2.31).

A massive, coarse to very coarse-grained, orange-stained, concretionary sandstone bed occurs between 8 and 13 m (Figure 2.33). A further sequence of interbedded fine- to medium-grained sandstones and carbonaceous siltstones occurs between 13 and 16.6 m containing carbonaceous leaf compressions and impressions. Poorly preserved parallel horizontal laminations and planar cross-stratification (18→037') also occur within this sequence.

A massive, coarse-grained sandstone bed dominates the upper 8 m of the section containing pebbles and carbonaceous streaks concentrated near the lower erosional contact and distributed sparsely throughout. The top of the bed fines, over approximately 1 m, to a fine-grained, highly cemented sandstone weathered to a light pink colour.

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1 Dip and dip direction of foresets.
Figure 2.32  Rose diagram to show the orientation of horizontal fossilised tree trunks within the fossil forest floor horizons of the shore platform at Curio Bay, Southland. The rose diagram is divided into 18 bi-directional sectors (each 20°) with a 1% scale. Each data point is plotted around the circumference and listed in Table D19, Appendix D.

Figure 2.33  Photograph to show the massive, coarse- to very coarse-grained, orange-stained, concretionary sandstone bed within the Curio Bay section, Southland. Figure = 1.82 m tall.
The fossil flora observed in the strata at Curio Bay is dominated by in-growth-position fossilised tree stumps and prostrate fossilised tree trunks exposed on the shore platform approximately parallel to a Temaikan forest floor. The prostrate fossilised trunks range from 0.05 to 0.50 m in diameter and have been recorded up to 30 m in length (Park, 1887). Diameters of the in-growth-position fossilised tree stumps are discussed in Section 4.44. The following description of the fossil forest exposure includes features observed by Raine and Pole (1988), Pole (1999) and the author.

All of the fossilised stumps within the well-exposed lowermost fossil forest horizon are rooted in a fine-grained sandstone, but preserved within an overlying medium-grained sandstone containing abundant streaks of carbonaceous material and many prostrate fossilised tree trunks. Many of the smaller fossilised stumps have elliptic cross-sections possibly due to post-depositional regional shear.

The fossilised stumps are preserved by cellular permineralisation and have weathered to a yellow colour (Figure 2.34). The outer rims of the fossilised stumps and trunks are commonly diffuse, possibly due to decomposition of the bark prior to fossilisation. The resistant fossilised stumps are exposed in relief against the shore platform and stand between approximately 0.3 and 1.8 m in height (Park, 1887; personal observation, 1998). Pole (1999) also observed rare carbonaceous tree-fern stumps rooted amongst the fossil tree stumps. Rarely, silicified roots several centimetres wide can be traced downwards.
and laterally from fossil stump bases into a poorly defined palaeosol (Figure 2.34). Fossilised growth rings are clearly visible in the cross-sections of many of the larger fossilised tree stumps but, without sampling (p. 64), an accurate method of measuring growth rings was not available. Pole (1999) used a portable binocular microscope in the field and although providing detailed measurements required a good wave-polished surface. In addition to fossilised wood, poorly preserved carbonaceous compressions of leaf fragments occur within the upper half of the section and well-preserved fossil spores and pollen have been derived from carbonaceous siltstone beds (Figure 2.31).

Figure 2.34  Fossilised tree stump still in growth position with silicified roots (arrowed) radiating downwards into the palaeosol from the stump base. Hammer = 32 cm long.
Depositional Environment

The Temaikan sediments exposed at Curio Bay are interpreted to have been deposited on a well-drained fluvial plain (Pole, 1999). The prostrate fossilised tree trunk orientation data suggests a consistent north-west/south-east trending palaeoslope. However, there is no direct evidence for the palaeoflow direction. Massive sheet floods depositing vast quantities of volcanioclastic debris and possibly ash falls from volcanic eruptions are considered to have caused the destruction of the forests (Raine and Pole, 1988; Pole, 1999). The poor preservation of sedimentary structures in the strata at Curio Bay prevents a detailed facies analysis at this locality. However, Figure 2.35 presents a model of the depositional environment based on previous work and the sedimentology and palaeobotany of the stratigraphic section.

Figure 2.35  A model of the depositional environment for the Curio Bay fossil forest deposits. Modified from Walker and Cant, 1984.
2.4 SUMMARY

Chapter 2 presented a sedimentological analysis of the Temaikan Urawitiki Measures strata exposed at Kawhia Harbour and a summary of information interpreted about the approximately coeval sediments at Curio Bay in Southland. The Urawitiki Measures formation, deposited slowly on a fan-delta and then more rapidly on a sandy braidplain represents a much longer period of deposition than the river-deposited sediments in the short measured section at Curio Bay. A quantitative estimation of sedimentation rate is not possible due to qualitative dating and the loss of unknown periods of sedimentation at erosional contacts within each sequence.

Shallow marine and subaerial fan-delta facies interpreted for the lower portion of the Urawitiki Measures (West Coast section, Te Maika Peninsula) are not observed in the Curio Bay strata. However, the lithologies at Curio Bay are similar to those within the facies of the uppermost Urawitiki Measures implying both sedimentary sequences were deposited by rivers. The poor preservation of the sedimentary structures at Curio Bay only allows a broad interpretation of the depositional environment compared with the Urawitiki Measures. For example, the meandering river and floodplain model interpreted for Curio Bay (Figure 2.35) could well have been a braided river setting instead due to the high proportion of sandstone compared to siltstone. However, the consistent cycles of sandstone/siltstone/coal throughout the section are typical of regular channel migration and fill facies in a meandering river system (Boggs, 1995).
Similarities between the lithologies at both Kawhia Harbour and Curio Bay include the comparable weathering of the dominant volcaniclastic sandstones into orange-stained concretions above the splash zone. Further, the siltstones are highly carbonaceous at both localities and contain common fossil plant organs of spores, pollen and leaf fragments. The coal beds are very thin at both localities suggesting that a wet and dry season affected both sites each year (p. 137). In addition, the pebbly sandstones, abundant fragments of carbonaceous plant material and the complete silicification of even the largest stumps at Curio Bay implies that the process of forest inundation and preservation was similar to that interpreted for the Urawitiki Measures (Figure 2.231).

The description of the fossil-forest-bearing strata at Kawhia Harbour and Curio Bay implies that the depositional settings at both sites were comparable during the Temaikan. The Curio Bay sediments could well have been deposited closer to the coast than those exposed at the tip of Te Maika Peninsula in Kawhia Harbour, possibly where braided streams flowing from the source mountains had stabilised into a meandering river flow. Despite the possible slight difference in age between the Curio Bay and Kawhia deposits (p. 44), the general depositional setting of a coastal plain with rivers transporting eroded volcaniclastic material from the arc mountains to the coast of Gondwanaland could well have been persistent throughout the Temaikan and possibly until the end of terrestrial deposition in the Murihiku Basin in the Upper Jurassic (p. 134).
CHAPTER 3

PALAEOGEOGRAPHY & GEOLOGICAL HISTORY

3.1 PALAEOGEOGRAPHY

The palaeogeographical context of the Urawitiki Measures and synchronous formations in the Kawhia Harbour region can be reconstructed from the sedimentological investigation and depositional environment interpretation. Temaikan Rengarenga Group formations, including the Urawitiki Measures, crop-out in three separate areas within the Kawhia Regional Syncline (Table 3.1 and Figure 3.1). The sediments are distinct in these areas, having been deposited in different depositional environments and are described as separate formations (Waterhouse and White, 1994). Outcrop depends on location with respect to the major north/south trending faults and broad folds within the Kawhia Regional Syncline (Figure 1.32).

Upper Triassic-Upper Jurassic sediments in the Kawhia Harbour region (Figure 1.32) all decrease in grain size towards the north-east and east. This change in grain size suggests a palaeo-coastline almost parallel to the present, with depositional environments becoming offshore to the east. The interpretation of the Urawitiki Measures sediments at Te Maika Peninsula implies the eastward progradation of a fan-delta from high relief source mountains in the west into the north/south trending Murihiku basin (Section 2.24) and is in agreement with this general palaeogeography.
Table 3.1  Rengarenga Group formations, listed in stratigraphic order, cropping-out in three separate areas within the Kawhia Regional Syncline. There are no definite lateral correlations. After Waterhouse and White, 1994.

<table>
<thead>
<tr>
<th>Albatross Point fault block, west of Wairere Fault¹</th>
<th>West of Kawaroa Anticline, east of the Wairere Fault</th>
<th>East of the Kawaroa Anticline, west of the Waipa Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaiate Formation</td>
<td>Wharetanu Measures</td>
<td>Wilson Sandstone</td>
</tr>
<tr>
<td>Te Angina Formation</td>
<td>Opapaka Sandstone</td>
<td>Putau Siltstone</td>
</tr>
<tr>
<td>Tokatapu Sandstone</td>
<td>Urawitiki Measures</td>
<td>Ohautira Conglomerate</td>
</tr>
<tr>
<td>Waioioi Formation</td>
<td></td>
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</table>

Correlation between the afunal terrestrial Rengarenga Group formations in the region can only be estimated based on sedimentary characteristics and the occurrence of ingrowth-position fossilised tree stumps². During the early-mid Temaikan, regional formations interpreted as being synchronous with the Urawitiki Measures, include the Waioioi Formation (Albatross Point fault block, west of the Wairere Fault) and the Ohautira Conglomerate (east of the Kawaroa Anticline, west of the Waipa Fault). The Waioioi Formation lithologies, particularly the conglomerate lenses, appear comparable to the lowermost Urawitiki Measures sediments and are similarly interpreted as terrestrial but possibly shallow marine in origin (Waterhouse and White, 1994). The Ohautira Conglomerate is interpreted as a near-shore marine deposit (Waterhouse and White, 1994).

¹ Synonymous with the Taharoa Fault of Suggate, 1978.
² Only relatively long-living Middle-Upper Jurassic plants are found in these formations, for example Cladophlebis spp. and Taeniopteris spp. (Waterhouse and White, 1994) which negates the use of fossil macroflora for dating. Temaikan microfloral biostratigraphy is in progress by Raine and de Jersey (pers. commun., 1998).
Figure 3.1  Map of the Kawhia Harbour region with outcrops of Temaikan Rengarenga Group formations. Outcrop occurs in three areas: the Albatross Point fault block, west of the Wairere Fault; west of Kawaroa Anticline, east of the Wairere Fault; east of Kawaroa Anticline, west of the Waipa Fault. Major north/south striking fold axes and faults are marked, plus localities referred to in the text. Map modified from Suggate, 1978.
White, 1994). All three formations can be interpreted to represent the maximum extent of land along the continental margin of the Murihiku basin in the Kawhia region during the early-mid Temaikan. The palaeo-coastline would have traced approximately parallel to the outcrop pattern between the definitely terrestrial Urawitiki Measures and the near-shore marine Ohautira Conglomerate to the east. Therefore, by rotating the strata in the Kawhia Regional Syncline back to horizontal, the maximum west/east subaerial extent of the Urawitiki Measures fan-delta lobe reached at least from the present day coastline (at Albatross Point) to a palaeo-coastline between ~15 and 45 km to the east. There is no evidence of terrestrial sedimentation to the east of Totara Peninsula (the Wharetanu Measures) during the Temaikan, so the palaeo-coastline can only be plotted to this extent in the reconstruction (Figure 3.2).

The correlation of Temaikan formations to the north and south of Kawhia Harbour is not possible in the Albatross Point and Te Maika Peninsula outcrop areas due to lack of exposure. Approximately 25 km to the south of Te Maika Peninsula, undifferentiated Rengarenga Group sediments in the Marakopa Valley (Figure 3.1) contain rare fossilised tree stumps (Macfarlan, 1975) implying terrestrial sedimentation. However, these are not preserved in-growth-position and may have been transported some distance before deposition. Further north near Te Akau, and along strike from the Ohautira Conglomerate, glauconitic sandstones have been interpreted as equivalent to the terrestrial strata of the Urawitiki Measures (Figure 3.1; Henderson and Grange, 1926). In addition, one specimen of Pseudauccella marshalli Trechmann was discovered in sediments adjacent to the glauconitic sandstone at Te Akau. However, this limited
Figure 3.2 Palaeogeographical map (grey), superimposed on to an outline of the present day coastline and Rengarenga Group outcrops (black) in the Kawhia Harbour region to show the extent of land in an easterly direction from the Temaikan arc source mountains. The palaeo-coastline is placed just east of the truly terrestrial strata containing in-growth-position fossil vegetation at Te Maika and Totara Peninsulas (the Urawitiki and Wharetanu Measures respectively). However, the maximum extent of land during the Temaikan could well have continued eastwards, but no further than the site of deposition of the near-shore marine Ohautira Conglomerate. The scale of the palaeogeography would have been exaggerated, in a west-east direction, upon flattening of the folded Mesozoic strata.
evidence is insufficient to locate a palaeo-coastline through this location. The palaeo-
coastline, at the time of Urawitiki Measures deposition, could well have been west of,
but approximately parallel to, the present-day coastline. Except in the Te Maika and
Totara Peninsula regions there is no evidence of fan-delta lobes prograding from the arc
mountains, but the facies analysis and depositional environment reconstruction of the
upper Urawitiki Measures (Figure 2.230) suggests the possibility of a strip of coalesced
fans which lay parallel to the palaeo-coastline, perhaps with merged fan-toes forming a
braidplain between the margin of the Murihiku basin and the arc mountains.

The westward extent of the fan-delta, or the distance to the source mountains, could be
estimated using Barrett and Fitzgerald’s (1985) formula which relates the estimated
percentage weight loss of a pebble, quantified by pebble roundness, to the distance of
downstream travel. Sneed and Folk (1958) discovered that quartz-rich pebbles reach a
limiting roundness index of ~0.65 after 240 km of travel. However, average pebble
roundness values calculated from all the conglomerate beds, except Conglomerate A,
within the West Coast section on Te Maika Peninsula are >0.65 (Table D14, Appendix
D). The implied bedload transport distance of >240 km seems unlikely if the Murihiku
basin was sourced from an oceanic arc, which may only have been approximately 300
km wide (Coombs, et al., 1996). Application of Conglomerate A’s average pebble
roundness to Barrett and Fitzgerald’s (1985) equation is unrealistic as variables involved
in the calculation are based on experimental data from limestone pebbles (Krumbein,
1941b) and abrasion coefficients with large error margins (Adams, 1978).
A quantifiable estimate of the distance to the source mountains from the site of deposition of the Urawitiki Measures conglomerates can be made by comparison with the Oretian (Upper Triassic) Moeatoa Conglomerate which crops-out on the coast 30 km south of the Kawhia Harbour entrance. The Moeatoa Conglomerate deposit is 1200 m (±120 m) thick and poorly sorted with boulders up to 90 cm long (Lowry, 1962). In contrast, the lowermost Urawitiki Measures contains thin, moderately to well-sorted pebble beds (each up to 4 m thick) with a much smaller clast size (up to 10.1 cm long). Therefore, the source of the Temaikan sediments is likely to have been much more distal than the 8-16 km estimated for the Oretian Moeatoa Conglomerate (ibid.).

In summary, the sedimentary characteristics of early-mid Temaikan formations within the Kawhia Harbour region, suggest the eastward progradation of at least one fan-delta from high source mountains in the west which may have merged with an adjacent fan-toe braidplain and become vegetated above marine influence, along the Murihiku basin margin. During this phase of deposition, the fan-delta actively prograded into the shallow marine basin over a gentle slope. Interpretation of the Urawitiki Measures sediments at Te Maika Peninsula, suggests first a northward and then an eastward lobe prograded into the braidplain at this locality. The occurrence of in-growth-position fossilised tree stumps at Te Maika Peninsula, plus fossil leaves in the Waioioi Formation, suggests a significant proportion of the subaerial merged fan-toe braidplain was vegetated.
The Kawhia and Southland Regional Synclines (prior to their separation by the Alpine Fault) represent adjacent deposition in the Murihiku basin on the Gondwanaland margin. Temaikan formations in the Southland Regional Syncline have been shown to coarsen to the south-west and mudstone sequences thicken to the north-east implying a shoreline to the west (Speden, 1971), correlating with the interpretation from the Kawhia region. The comparable depositional environments of the fossil-forest-bearing strata at Kawhia Harbour and Curio Bay represent close to the northernmost and southernmost extent of the Murihiku basin sedimentary record in New Zealand, implying a well vegetated coastline over the whole region.

3.2 GEOLOGICAL HISTORY

The Jurassic strata cropping-out in the Kawhia Harbour region reflect successive cycles of marine transgression and regression which caused periodic inundations of the vegetated Murihiku basin margin fan-delta complex. Following each sea level retreat, the fan-delta and braidplain surface would be re-colonised by diverse and abundant vegetation.

Immediately prior to the deposition of the Urawitiki Measures, the mainly fine-grained sediments and marine faunas of the Ururoan Opango Formation (Newcastle Group, Figure 1.33), cropping-out on the lower west coast of Te Maika Peninsula, represent deposition that occurred in an offshore pro-delta or marine shelf depositional environment (Hudson, 1983). Aggradation and the consequent lowering of the
palaeoslope gradient, throughout the lowermost Urawitiki Measures, is reflected in the shallowing of marine depositional environments, ultimately becoming terrestrial. Facies indicate a transition from a subaqueous fan-delta front to subaerial upper alluvial mid-fan facies, prior to the stratigraphic gap between the lowermost and uppermost Urawitiki Measures strata at the tip of Te Maika Peninsula. The marine to terrestrial transition also suggests the occurrence of an active, prograding fan-delta front, possibly due to a period of tectonic uplift that increased sedimentation throughout deposition of the Opango Formation and the lowermost Urawitiki Measures.

During deposition of the sediments in the stratigraphic gap between the lowermost and uppermost Urawitiki Measures, tectonic movement reversed and a period of gradual subsidence began which continued until the deposition of the Opapaka Sandstone. The abundant sediment supply from the source oceanic arc continued aggradation on the fan-delta complex, although the palaeo-coastline out to the east had already begun to advance westwards, or back inland. On the subaerial fan-delta braidplain at Te Maika Peninsula, vegetation colonised the interdistributary bars between braiding channels and was occasionally destroyed by major flooding. Due to the continual subsidence and therefore maintenance of a high water table, successive layers of fossilised tree stumps and flood deposits were preserved in the sedimentary record in the uppermost Urawitiki Measures sediments.

The period of tectonic subsidence that began in the middle of the Urawitiki Measures deposition culminated in a brief marine transgression which deposited the shallow
marine Opapaka Sandstone over the braided river sediments of the uppermost Urawitiki Measures formation. Despite only broad lithostratigraphic correlation between the Rengarenga Group formations of the Te Maika Peninsula area and those cropping-out in the Albatross Point fault block to the west, similar shallow marine sediments (?Te Angina Formation) occur suggesting that the coastline reached at least another 12 km inland before the next phase of uplift.

Following deposition of the Opapaka Sandstone, a further tectonic pulse caused the land to rise again, renewing river sedimentation and vegetation growth on the fan-delta and depositing the terrestrial facies of the Wharetanu Measures. After deposition of the Wharetanu Measures, the land again subsided during the late Temaikan, to a greater degree than during deposition of the Rengarenga Group, depositing the massive offshore marine siltstones of the Pakau Formation (Kirikiri Group; Figure 1.35). The final phase of tectonic uplift during the Jurassic and prior to the climax of the Rangitata Orogeny occurred during the Puaroan when the terrestrial Huriwai Group was deposited.

In summary, the terrestrial-marine depositional cycles throughout the Jurassic in the Kawhia Harbour region occurred in response to alternating periods of tectonic uplift and subsidence in the Murihiku basin. These tectonic events were the result of pulses of plate movement during the collision of the Torlesse Terrane and the accreted terranes along the Gondwanaland margin during the first stages of the Rangitata Orogeny (p. 47).

1 Calculated by reverting the sediments of the western limb of the Kawhia Regional Syncline to the horizontal.
Local changes in the proportions of marine and terrestrial deltaic sediments in the Temaikan of the Southland Regional Syncline could well represent similar events, but knowledge of their stratigraphic relationships is poor.
CHAPTER 4

VEGETATION RECONSTRUCTION

4.1 INTRODUCTION

Attempts to reconstruct vegetation from deposits of fossil plant remains becomes difficult when interpreting fossils older than the early Cenozoic. Information about the original plant becomes distorted or lost during taphonomy, preservation and eventual collection. To address this problem, a detailed taphonomic study is necessary. The natural affinity, life form reconstruction and association of the fossil plant organs with each other and a particular sedimentary facies allows an informed interpretation of the composition, structure and distribution of the source vegetation.

The fossil forest horizons exposed at Te Maika and Totara Peninsulas in Kawhia Harbour consist of abundant well-preserved fossil plant organs throughout stratigraphic sections that record many facies changes (Section 2.2). This allows a detailed taphonomic analysis of the fossil flora at this location and consequent interpretations about the nature of the source vegetation. The Curio Bay fossil forest horizons contain only a small quantity of fossil plant organs (despite diverse palynomorph assemblages and numerous fossilised tree stumps) which are generally poorly preserved, within a short stratigraphic section recording a relatively short period of sedimentation. Therefore, the Curio Bay fossil forest deposit is not suitable for a detailed taphonomic
analysis. However, similarities in depositional environment and composition of the fossil flora (Section 4.2) imply the taphonomic processes affecting the floral remains could well have been similar to those at Kawhia Harbour. The fossil forest structure at Curio Bay is also investigated and compared to that interpreted for the Urawitiki Measures at Kawhia Harbour.

**Table 4.1** Methods employed in the following section to reconstruct the vegetation cover present on the landscape during deposition of the uppermost sediments of the Urawitiki Measures, Kawhia Harbour.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Definition / Method</th>
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<tbody>
<tr>
<td>Systematics</td>
<td>Taxonomic classification of the fossil plant remains and an interpretation of their natural affinities.</td>
</tr>
<tr>
<td>Taphonomy</td>
<td>A study of the incorporation and preservation of the plant remains in the sediment to determine the extent of information loss from each assemblage.</td>
</tr>
<tr>
<td>Palaeogeobotany</td>
<td>An interpretation of life forms and the plant community in relation to the abiotic environment.</td>
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**4.2 SYSTEMATICS**

**4.21 Introduction**

The following section describes the systematics of the previously unstudied fossil plants from the Urawitiki Measures stratigraphic sections in Kawhia Harbour (Enclosures 1 to 5) and specimens collected by the author from approximately coeval strata in Curio Bay, Southland. Additional Southland collection localities included Temaikan strata at Slope
Point (Figure 1.310) and Waipapa Point (12 km west of Slope Point). The entire fossil flora collection consists of dispersed terrestrial palynomorphs (fossil spores, pollen and associated palynodebris), fossilised seeds, seed cones, leaves, leaf and cone scales, herbaceous stems, trunks and stumps. Laboratory investigative methods are described in Appendix E with difficulties encountered during their application. The sample numbers quoted refer to the School of Earth Science, Victoria University of Wellington collection numbers and each listed or figured specimen or palynological sample can be stratigraphically located by reference to the stratigraphic sections (Enclosures 1-5; Figures 2.31 and 4.41).

The systematic descriptions are divided into *Fossil Macroflora* (excluding fossil wood), *Fossil Wood* and *Fossil Microflora* (spores, pollen and palynodebris) organ groups. *Fossil Microflora* systematic descriptions can be found in Volume 2 (Appendix G). All illustrative plates are also located in Volume 2. All three sections include a general description of the fossil material collected, the state of preservation and relevant previous studies used for identification purposes. A description of wood histology and the formation of growth rings introduces the *Fossil Wood* section to clarify terminology. The natural classification scheme, in all sections, follows that of Stewart and Rothwell, 1993. To summarise, a synopsis of the overall taxonomic composition of the fossil flora at both the Kawhia Harbour and Curio Bay localities is presented and a comparison made with other Jurassic Southern Hemisphere floras.
4.22 Fossil Macroflora (excluding fossil wood)

Introduction

Fossilised remains of macro-plant organs, other than fossil wood, are found predominantly in fine-grained lithologies (siltstones and sandstones) and occur throughout the uppermost Urawitiki Measures at Kawhia Harbour. Fossil plant organs from this locality described in the following section include stems, leaves, a fern scale, seeds and seed cones of the Bryopsida, Filicopsida and Gymnospermopsida classes. All the specimens, except Ashicaulis sp. (VH192), are preserved as coalified compressions (where the organic matter remains) or impressions (where the organic matter has been removed). Cellular detail from this mode of preservation is generally poor and cuticular detail was not preserved on the leaf laminas. However, sufficient detail of venation patterns remain for classification. VH192 is preserved by cellular permineralisation. This process involves cellular structure permeation by a silica-rich fluid, at or very soon after burial, and the rapid precipitation of colloidal or microcrystalline silica (Schopf, 1975). Although altered, much of the organic matter remains and cellular detail is often extremely well preserved.

Fossil plant organs, other than fossil wood, found in sediments of the Curio Bay region include stems and leaves derived predominantly from siltstone lithologies. The fossil plants represent relatives of the Sphenopsida, Filicopsida and Gymnospermopsida Classes. The majority of the specimens are poorly preserved as carbonaceous
compressions or impressions, but the Ashicaulis gibbiana (Kidston & Gwynne-Vaughan) Tidwell, 1994 (sample VH262) and several ?Ashicaulis sp. specimens are preserved by cellular permineralisation in silica.

Systematic Descriptions

DIVISION BRYOPHYTA, CLASS ?BRYOPSIDA

Gen. indet.

Plate 1, Figure 1.

Sample number: VH167.

Description:

Stem-like structures 0.5-0.8 mm diameter, up to 9.0 mm long. Leaf-like parts up to 4.3 mm long, 0.2 mm wide, with thin, flattened lamina perpendicular to long axis of stem-like part, but no midrib (preservation is poor). Leaves in a spiral arrangement from the main axis, no branching is evident.

Remarks:

A rare example of a Mesozoic bryophyte, this specimen represents a leafy moss gametophyte. With no observable midrib, the assignment to Bryopsida is uncertain.
Known New Zealand Jurassic Occurrence:

Middle Jurassic: Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Regional Syncline (this thesis).

DIVISION TRACHEOPHYTA, CLASS LYCOPSIDA, ORDER ?LYCOPODIALES

FORM GENUS Lycopodites Brongniart, 1822

?Lycopodites sp.

Figure 4.21(a).

Description:

Unbranched silicified stem, 28.9 cm long, 2.5 cm wide with alternating leaf scars of lycopod form. Specimen compressed to a veneer with indefinite margins and preserved within a matrix-supported pebbly conglomerate. Not collected.

Remarks:

Classification of this specimen is uncertain due to poor preservation, but provides a fossil macroflora record of the Lycopsida within the Curio Bay region. The specimen may represent Lycopodites arberi Edwards, 1934 described from a collection site just inland from Curio Bay (Edwards, 1934), but a lack of detail means a comparison cannot be made. Lycopodites is thought to have had a herbaceous habit similar to living species of both Lycopodium and Selaginella (Edwards, 1934).
Known New Zealand Jurassic Occurrence:

Middle Jurassic: Slope Point, Southland Regional Syncline (this thesis).

CLASS SPHENOPSIDA, ORDER Equisetales, FAMILY Equisetaceae

GENUS Equisetites Sternberg, 1838

Equisetites hollowayi Edwards, 1934

Figure 4.21(b).

Sample number: VH257

Description:

Several unbranched stems, 0.4-0.5 cm diameter, up to 7.2 cm long. Internodes 2.3-2.8 cm long with fine ribs parallel to the stem long axis. No leaves preserved.

Remarks:

The size of the stems, length of the internodes and fine ribs preserved in this specimen compare well to the original diagnosis (Edwards, 1934), despite the lack of leaves. The fine ribbing distinguishes this specimen from Equisetites nicoli Arber, 1917.

Known New Zealand Jurassic Occurrence:

Middle Jurassic: Curio Bay, Southland Regional Syncline (Edwards, 1934; this thesis);

Upper Jurassic: Port Waikato, Kawhia Regional Syncline (Edwards, 1934).
Figure 4.21 Lycopod- and horsetail-related fossils from the Temaikan of the Southland Regional Syncline.

a)  *?Lycopodites* sp. stem fragment, Slope Point. Stem = 29 cm long.

b) Line drawings of *Equisetites hollowayi* Edwards, 1934 stem fragments. Sample VH257, Curio Bay. Both stems are 5 mm wide.
CLASS FILICOPSIDA, ORDER FILICALES, FAMILY OSMUNDACEAE

SUB-FAMILY OSMUNDOIDEAE Zhong Ming Li, 1993,

GENUS *Ashicaulis* Tidwell, 1994

*Ashicaulis gibbiana* (Kidston & Gwynne-Vaughan) Tidwell, 1994

Plate 2, Figures 1,2.

Sample number: VH262

Description:
Extremely well preserved rhizome fragment, elliptical in cross-section, 59x40 mm. Silicified with cryptocrystalline silica, preserving minute cellular details. Xylem ring visible in core with an outer sclerotic region (cortex), surrounded by mantle of tightly packed, concrescent leaf traces and rootlets arranged in a spiral arrangement about the core. Affected by compression - leaf traces and xylem ring flattened in one direction (perpendicular to the long axis of the elliptic cross-section). Parenchyma cells of central pith (within xylem ring) or within the sclerotic ring of the leaf traces is not preserved. Grains of fine sand have infilled some of these voids. The inner cortex and peripheral tissues of the stele (including the phloem) have also not preserved, but the fibrous sclerotic elements of the outer cortex are well preserved and individual lumina are visible.

Individual xylem strands are mainly separate, the gaps would have developed into medullary rays (Plate 2, Figure 1). The tracheid cells of the xylem are of similar
diameter throughout each strand. Numerous leaf bases can be seen traversing the outer cortex and three are budding from the xylem ring (Plate 2, Figure 1). Near the specimen periphery, the leaf traces have the shape of a horseshoe with deeply inrolled ends. Protoxylem groups are not distinguished due to compression in the outer regions of the specimen. The distribution of scattered sclerotic strands within the leaf traces is difficult to determine due to compression, but one petiole arrangement does not appear to be paired. There are no leaf scales. Roots arise from the margins of the leaf traces in the inner cortex and grow laterally (Plate 2, Figure 2); seen in transverse section towards the periphery.

Remarks:
Although preservation of many cellular details is incomplete (for example, the parenchyma and inner cortex) the mainly separate xylem strands, the similar diameter of the tracheids within the xylem and the lack of paired sclerotic strands within the lateral bays of the leaf traces distinguishes this specimen from *Ashicaulis dunlopi* (Kidston & Gwynne-Vaughan) Tidwell, 1994. Both species were originally described from Curio Bay (Kidston and Gwynne-Vaughan, 1907). The stem is smaller than the specimen originally described but this could well be due to the age of the plant and not a diagnostic feature.

**Known New Zealand Jurassic Occurrence:**
Middle Jurassic: Curio Bay vicinity (Kidston and Gwynne-Vaughan, 1907); Slope Point, Southland Regional Syncline (this thesis).
?Ashicaulis sp.

Figure 4.22; Plate 5, Figures 3,4.

Sample numbers: VH137, VH147, VH148, VH192.

Description:

Samples VH137, VH147 and VH148: silicified (Plate 5, Figure 3) and carbonaceous (Plate 5, Figure 4) rhizome fragments. Fibrous appearance, suggestive of central vascular strand surrounded by petiole bases and aerial roots. No cellular detail preserved. Rhizome fragments up to 180 mm long and 45 mm wide. Similar specimens were observed, but not collected, within the Opapaka Point section, Te Maika Peninsula and at Curio Bay. One specimen at Curio Bay, also left in situ included a rhizome fragment 287 mm long and 40 mm wide.

Sample VH192 (Figure 4.22): silicified rhizome fragment. Densely packed petiole bases, aerial roots not identified. Specimen to one side of core of stem as no central xylem cylinder present. Transverse section of petiole bases - rounded, oblong to elliptical (up to 5 mm long, 3 mm wide), vascular strand originally C-shaped. Distorted and largely recrystallised, so no cellular detail preserved.
Figure 4.22 (a) Side and (b) transverse (polished surface) view of Ashicaulis sp. rhizome fragment. Sample VH192, Urawitiki Measures, Kawhia Harbour. Magnification x 1.

Remarks:
Structurally preserved fossilised rhizome fragments assigned to Ashicaulis (A.) Tidwell, 1994 are diagnosed as stems surrounded by a mantle of leaf bases and roots with a xylem cylinder dissected by many definite leaf-gaps (Tidwell, 1994). Miller (1967) describes the leaf traces as oblong, or adaxially curved in transverse section. Further, the vascular strand in the petiole base is C-shaped in transverse section and the xylem strand of the root is diarch (ibid.). The shape of rare undistorted leaf traces and petiole xylem strands in transverse section in the silicified specimen (VH192) suggests that it can be assigned to this genus. The carbonaceous stems, although devoid of such details, are assignable to A. due to the similarity in size and external appearance of the rhizome fragments.

Fossil Osmundaceae have been described in sediments ranging from late Permian to late Tertiary in age (Miller, 1967), with a similar stem structure to living forms (Meyen, 1987). The fertile, fossil form genus Todites, with laminate fronds and osmundaceous sporangia, is grouped with the sterile Cladophlebis (C.) type frond (Harris, 1961), suggesting an osmundaceous origin for the latter. Despite both osmundaceous rhizome
fragments and C. type fronds in the uppermost Urawitiki Measures, there were no organic connections and no direct evidence for this relationship.

**Known New Zealand Jurassic Occurrence:**

Middle Jurassic: Ohanga Bay sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis); Curio Bay, Southland Regional Syncline (this thesis).

**FAMILY ?OSMUNDACEAE**

**FORM GENUS Cladophlebis** Brongniart, 1849

*Cladophlebis* cf. *australis* Morris, 1845

Figures 4.23, 4.24; Plate 1, Figures 2-4; Plate 3, Figures 1,2; Plate 4, Figures 1,2.

**Synonymy:** See Broekhuizen, 1984.

**Sample numbers:** VH150-159, VH196

**Description:**

Bipinnate frond fragments. Pinna oblique-perpendicular to the rachis, which was observed up to 15 mm in diameter (Figure 4.23(a); Plate 1, Figure 2). Pinnules vary in size up to 26.0 mm long, 6.5 mm wide. Away from the pinna apex, and closer to the site
Figure 4.23 Gross morphology of *Cladophlebis* cf. *australis* Morris, 1845 from Urawitiki Measures, Kawhia Harbour, specimens as indicated, showing the varying pinnule outlines, branching and attachment features along the length of a pinna. Lateral venation is not presented (refer to Figure 4.24).
of attachment to the rachis, pinnules are long, linear-oblong (rarely falcate) with rounded, frequently denticulate margins at the apices. Pinnules branch at a large angle, often perpendicular, to the pinna midrib. They are predominantly adnate and distinctly separate from neighbouring pinnules (for example, Figure 4.23(b); Plate 1, Figures 3,4). Towards the apex, the pinnules branch at progressively steeper angles from the pinna midrib (for example, Figure 4.23(c); Plate 3, Figures 1,2), until close to the pinna apex, they branch at smaller angles, are shorter and falcate with pointed, rarely denticulate margins at the apices. Here, the pinnules are much closer together and decurrent in attachment to the midrib (for example, Figure 4.23(d); Plate 1, Figure 3). In all pinnules, branching from the pinna midrib is alternate (for example, Plate 3, Figure 2), the lateral venation is free, extends to the margin and is both once and twice bifurcating throughout the pinnule length. Close to the pinnule apex, the central vein splits and simple, unbranched veins extend to the margin (Figure 4.24; Plate 4, Figures 1,2).

Figure 4.24  *Cladophlebis cf. australis* Morris, 1845. Detail of lateral venation to show inconsistent bifurcation throughout the pinnule lengths. Sample VH153a, Urawitiki Measures, Kawhia Harbour.
Remarks:

The Cladophlebis (C.) frond form is common in both fossilised and modern fern families, and many C. species are thought to have an affinity with the Osmundaceae (Broekhuizen, 1984). *C. australis* Morris, 1845, originally described from the Triassic of Tasmania (Morris, 1845), has been applied to many frond specimens of the *C.* form within Gondwanaland sediments and is wide-ranging throughout the Mesozoic. It is likely that specimens named as this species actually represent many different species (Retallack, 1983). However, the criteria for separating these closely related forms has yet to be decided. Minor differences in form, for example, lateral venation bifurcation or margin denticulation, were not favoured as valid methods of distinction by early workers (for example, Seward, 1904; Arber, 1917) but consistent differences in such features between specimens were thought justifiable in later studies (Broekhuizen, 1984).

The type specimen of *C. australis* Morris, 1845 was described as having consistently twice bifurcating lateral veins throughout the pinnules, although Arber’s (1917) specimens have both once and twice bifurcating veins. Broekhuizen (1984) describes fern fronds in the Huriwai Group flora (Upper Jurassic, cropping-out near Port Waikato, approximately 80 km north of Kawhia Harbour) as having venation that normally forks once, may be simple close to the pinnule apex and basal veins that often fork twice. One branch of the first bifurcation may fork again, particularly in the lower parts of the frond or in large pinnules. Broekhuizen (1984) recombined this form as *C. hochstetteri* (Unger), which has previously been described from Victoria (Herbst, 1978 (named *C. australis* Morris, 1845); Douglas, 1969). The venation pattern of the Urawitiki
Measures fronds is intermediate between these forms, with both once and twice bifurcating veins, throughout the length of the pinnule, not consistent throughout, or restricted to the basal veins. The occurrence of this form in the Middle Jurassic, suggests an evolutionary trend of vein simplification within this form genus, from a wholly twice bifurcating form in the Triassic, to a normally once bifurcating form in the Upper Jurassic.

Arber's (1917) amended diagnosis of *C. australis* Morris, 1845 also states that the pinnule margins are entire and not toothed. Specimens from the Urawitiki Measures and those from the Huriwai Group Flora (Broekhuizen, 1984) both occasionally show slight denticulate margins near the apices of the pinnules. Table 4.2 summarises the venation and margin denticulation observed in these three forms.

Therefore, on the basis of a differing venation pattern and the presence of occasional denticulation near the apices in some pinnules, the Urawitiki Measures fronds are compared to *C. australis* Morris, 1845. The author does not think it is necessary to add to the already lengthy list of species assigned to this genus, on the basis of relatively minor features.

*Known New Zealand Jurassic Occurrence:*

Middle Jurassic: Ohanga Bay sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis).
New Zealand occurrences of *C. australis* Morris, 1845 (from Upper Triassic to Lower Cretaceous), include coeval strata at Albatross Point, Kawhia Harbour (Martin, 1975) (Figure 3.1) and the Curio Bay plant beds, Southland (Figure 1.310; Edwards, 1934).

Table 4.2  Pinnule venation and margin denticulation in *Cladophlebis* frond forms.

<table>
<thead>
<tr>
<th>Age</th>
<th>Mid-late Triassic</th>
<th>Mid Jurassic</th>
<th>Late Jur. / Early Cret.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location and authors</strong></td>
<td>Tasmania (Morris, 1845; Townrow, 1965) South Canterbury, South Island, New Zealand (Retallack, 1983)</td>
<td>Kawhia Harbour, North Island, New Zealand (this thesis)</td>
<td>Port Waikato, North Island, New Zealand (Hochstetter, 1964; Broekhuizen, 1984) Victoria, Australia (Herbst, 1978; Douglas, 1969)</td>
</tr>
<tr>
<td><strong>Pinnule margins</strong></td>
<td>Entire</td>
<td>Entire for length of pinnule, occasionally denticulate near apex.</td>
<td>Entire for length of pinnule, occasionally denticulate near apex.</td>
</tr>
<tr>
<td><strong>Venation</strong></td>
<td>Consistently twice forking</td>
<td>Both once and twice bifurcating, lateral veins throughout length of pinnule</td>
<td>Predominantly once bifurcating lateral veins, occasionally one or two twice bifurcating veins at base of pinnule</td>
</tr>
<tr>
<td><strong>Species</strong></td>
<td><em>C. australis</em> Morris 1845</td>
<td><em>C. cf. australis</em> Morris 1845</td>
<td><em>C. hochstetteri</em> (Unger) Broekhuizen, 1984</td>
</tr>
</tbody>
</table>

*Cladophlebis* cf. *denticulata* Brongniart, 1828

Plate 5, Figures 1,2.

**Synonymy:** See Boreau and Doubinger, 1975.

**Sample numbers:** VH149, VH185, VH194.
Description:

Description as for *Cladophlebis* (C.) cf. *australis* Morris, 1845, except for consistently denticulate margins along the entire length of the pinnules. Pinnules up to 15 mm long and 6 mm wide. No rachis was observed.

Remarks:

As noted by Arber (1917), specimens of *C. denticulata* Brongniart, 1828 differ from *C. australis* Morris, 1845 only in their denticulate pinnule margins. Therefore, with reference to the Remarks for *C. cf. australis* Morris, 1845, these specimens from the uppermost Urawitiki Measures can only be compared to *C. denticulata* Brongniart, 1828.

Known New Zealand Jurassic Occurrence:

Middle Jurassic: Southern Ohanga Bay and Jetty sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis).

New Zealand occurrences of *C. denticulata* Brongniart, 1828 include coeval strata at Albatross Point, Kawhia Harbour (Martin, 1975).

*Cladophlebis* spp.

Figure 4.25.

Sample numbers: VH184, VH195, VH256, VH260
Description:

Fragmented portions of *Cladophlebis*-type fronds, but with little or no venation detail preserved (Figure 4.25). Linear-oblong shaped pinnules, with a simple midrib and alternate branching.

![Fragmented pinnules](image)

**Figure 4.25** Examples of poorly preserved specimens assignable to the *Cladophlebis* form genus from the Urawitiki Measures, Kawhia Harbour. (a) Sample VH195; (b) Sample VH184a; (c) Sample VH184b.

Remarks:

All fragmented and poorly preserved fronds of this type from the uppermost Urawitiki Measures and poorly preserved frond fragments from Curio Bay are included within this form genus.

*Known New Zealand Jurassic Occurrence:*

Middle Jurassic: Jetty section, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis); Curio Bay, Southland Regional Syncline (this thesis).
Fern Scale

Gen. indet.

Plate 6, Figure 1.

Sample number: VH166.

Description:
Carbonaceous fringed fern scale, 5 mm long, 1 mm wide (excluding fringe) in a siltstone matrix. Rounded basal attachment surface. Five hair-like extensions from upper surface, increasing in height, either side, to the centre.

Remarks:
Scales are outgrowths from the outer layer of cells and occur most frequently on the rhizomes or on young, coiled fronds. Scales are flat plates of cells and vary greatly in morphology. Specimen VH166 is characterised by a fringe of hair-like extensions. A lack of association with any other part of a fern plant renders this specimen assignable only to the wide-ranging class of Filicopsida.

Known New Zealand Jurassic Occurrence:
Middle Jurassic: Northern Ohanga Bay section, Te Maika Peninsula, K Kawhia Regional Syncline (this thesis).
CLASS GYMNOSPERMOPSIDA, ORDER CONIFERALES

FORM GENUS *Elatocladus* Halle, 1913a

*Elatocladus conferta* Oldham and Morris, 1863

Plate 6, Figures 2-4.

**Synonymy:** See Arber, 1917.

**Sample numbers:** VH138-146, VH184, VH193.

**Description:**

Free shoots, occasionally branched at a consistent angle of 50-60° from the main axis (Plate 6, Figure 4). Leaves arranged helically (but appear opposite), sessile, decurrent and up to 90° from the axis (Plate 6, Figures 2,3). Lamina oblong-linear, dorsi-ventrally flattened and widens to a rounded apex. Up to 6 mm long and 2 mm wide, with a single, simple midrib. Preserved with axes randomly orientated particularly in association with *Cladophlebis* frond types.

**Remarks:**

Morphologically identical shoots of the form genus *Elatocladus* Halle, 1913a (*E.*) are assigned to the Coniferales families of Cephalotaxaceae, Podocarpaceae, or Taxodiaceae; or Taxaceae of the Taxales Order, aided by the preservation of epidermal details. *E.* leaves are also associated with the genus *Tomaxellia*, a female cone of the Cheirolepidaceae family (Meyen, 1987). Due to the commonly occurring characteristics
of this type of foliage its natural affinity cannot be restricted to a single family. However, on the absence of Cephalotaxaceae and Taxaceae from both the fossil macro- and micro-floras at Kawhia Harbour, the low relative abundance of Taxodiaceae and Cheirolepidae pollen in the microflora and the common podocarp-affinity fossil wood (Section 4.23), the foliage is tentatively assigned to the Podocarpaceae.

*Known New Zealand Jurassic Occurrence:*

Middle Jurassic: Ohanga Bay, and *ex situ* in beach debris at this locality and Jetty sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis).

New Zealand occurrences of *E. conferta* Oldham and Morris, 1863 (from Upper Triassic to Upper Jurassic), include coeval strata at Curio Bay, Southland (Edwards, 1934).

*Elatocladus* sp.

Figure 4.26.

*Sample number:* VH259

*Description:*

Branched twig bearing fragments of poorly preserved shoots with helically arranged, oblong-linear leaves of the *Elatocladus* type. Whole twig 111 mm long, up to 3 mm thick.
Figure 4.26  Poorly preserved twig bearing remnant *Elatocladus* sp. foliage. Sample VH259, South Head, near Curio Bay, Southland. Magnification x1.

Remarks:

Preservation too poor to allow further classification.

Known New Zealand Jurassic Occurrence:

Middle Jurassic: South Head near Curio Bay, Southland Regional Syncline (this thesis).

Seed Cone

*Gen. indet.*

Plate 7, Figures 1,2.

Sample number:  VH122.

Description:

Squat seed cone, with circular transverse section and irregular outline (Plate 7, Figure 1).

Short axis (30 mm long) with elongate bracts (15-20 mm long) emerging at a steep angle
(up to 20°) from vertical. Dispersed seeds of type in sample number VH165 (this page) occur in association. Seed cones occur in pairs, with bases adjacent (Plate 7, Figure 2), but no organic connection observed.

**Remarks:**

Seed cones of this type were found concentrated in a single bed containing 46 visible specimens. The paired cones may have been attached by short, unpreserved stems reflecting the seed cone habit in life. Due to the presence of seeds similar to sample number VH165, it is assumed these seed cones are also of Podocarpaceae affinity.

**Known New Zealand Jurassic Occurrence:**

Middle Jurassic: Opapaka Point, Southern Ohanga Bay and Jetty sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis).

Seed-bearing Cone Scales

*Gen. indet.*

Figure 4.27, Plate 7, Figure 3.

Sample number: VH164.

---

1 Macerated seed cones yielded a barren palynomorph preparation.
Description:

Elongate, wedge-shaped scales tapering to a rhombic apex, at least 18 mm long (fragmented), 3.5 mm wide. Two parallel, linear furrows on smooth, flattened surface, terminate 2.5 mm from apex. Elliptical, seed-like structure (1.5 x 1 mm) occurs at base of scale, with an emerging tapered furrow (Plate 7, Figure 3).

Remarks:

The surface furrows may mark the site of seed attachment. The elliptical structure may represent a single seed, perhaps once attached to a wing, characteristic of extant conifer tree seeds (Figure 4.27). The specimens resemble the scale morphology of *Araucarites cutchensis* Feistmantel, 1876 which is wedge-shaped with a broad rounded or truncated apex. However, sample VH164 is elongate, not ovate in outline and is much smaller than those figured and described by Arber (1917). Therefore, the specimens from Te Maika Peninsula cannot be compared to this species. However, the general similarities in morphology allow a tentative assignment to the Araucariaceae family.

Figure 4.27  Diagram to illustrate the position and form of seed-bearing cone scales in extant conifer seed cones. Modified from Neushul, 1974.
Known New Zealand Jurassic Occurrence:

Middle Jurassic: Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Regional Syncline (this thesis).

Seeds

Gen. indet.

Figure 4.28, Plate 7, Figure 4.

Sample number: VH165.

Description:

Dispersed ovate seeds, up to 6 mm long and 2.5 mm wide. Embryo, cotyledons and megagametophyte discernible within at least one specimen (Figure 4.28; Plate 7, Figure 4). Associated with seed cones, cone scales, and Elatocladus-type foliage.

![Figure 4.28](image) Outline drawing of seed longitudinal section, showing constituent parts and the embryonic plant. Sample VH165, Urawitiki Measures, Kawhia Harbour.
Remarks:

Seeds could well have originated from the same plant as the *Elatocladus* foliage, but no organic connections were observed.

Known New Zealand Occurrence:

Middle Jurassic: Opapaka Point and Northern Ohanga Bay sections, Te Maika Peninsula, Kawhia Regional Syncline (this thesis).

ORDER CYCADALES

FORM GENUS *Taeniopteris* Brongniart, 1828

*Taeniopteris daintreei* McCoy, 1874

Plate 8, Figures 1-3.

Synonymy: See Arber, 1917.

Sample numbers: VH160-163.

Description:

Simple, fragments of leaves with a prominent midrib (Plate 8, Figures 1-3). Fragments up to 52 mm long and 9 mm wide. Linear in shape, with parallel, entire margins and rounded apices. Lateral vein preservation is very poor, but appears to extend perpendicularly from the midrib to the margins, both simple and once bifurcating.
Remarks:

Specimens assigned to Cycadales, are known mostly from leaf remains. Those that are simple leaves with a thick midrib, have numerous lateral veins emerging at an open angle and their epidermal structure is unknown are assigned to the form genus *Taeniopteris* (*T.*). The lateral vein characteristics and narrow leaves correlate with the original diagnosis of *T. daintreei* McCoy, 1874. They are found in association with *Cladophlebis* type fronds. Blaschke and Grant-Mackie (1976) postulate on the affinity of *T. daintreei* McCoy, 1874 with the Pentoxylales from the similarities of *Nipaniophyllum* from India with *T. daintreei* McCoy, 1874 from Port Waikato in New Zealand. However, no direct evidence for such an association is presented and requires further palaeobotanical investigation.

**Known New Zealand Jurassic Occurrence:**

Middle Jurassic: Ohanga Bay sections and *ex situ* in beach debris at this locality, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis).

New Zealand occurrences of *T. daintreei* McCoy, 1874 (from Upper Triassic to Upper Jurassic), include coeval strata at Albatross Point, Kawhia Harbour (Martin, 1975) and fronds of the same form genus within the Curio Bay plant beds, Southland (Edwards, 1934).
ORDER CYCADEOIDALES

FORM GENUS *Ptilophyllum* Morris, 1840

*Ptilophyllum acutifolium* Morris, 1840

Figure 4.29.

**Synonymy:** see Arber, 1917

**Sample number:** VH302

**Description:**

Portion of a pinnate leaf with elongate, sickle-shaped pinnules, 8-9 mm long, 2-4 mm wide (consistent size within each leaf fragment). Five to six subparallel veins arise from the pinna midrib, forking once near the base and extending towards the pinnule apex (Figure 4.29).

![Diagram of Ptilophyllum acutifolium](image)

**Figure 4.29** Pinnate frond fragments of *Ptilophyllum acutifolium* Morris 1840, Curio Bay, Southland. Scale bars = 1 cm. (a) Sample VH256; (b) Sample VH302.
Remarks:

Specimens assigned to *Ptilophyllum acutifolium* Morris, 1840 also occur within the same specimen as pinna fragments of *Cladophlebis* spp. (VH256).

**Known New Zealand Jurassic Occurrence:**

*Middle Jurassic: Curio Bay, Southland Regional Syncline (Arber, 1917; this thesis).*

**Summary**

The macroflora specimens (excluding the fossilised wood) described in the previous section reflect an unknown proportion of the local/extralocal composition of the original source vegetation at either Kawhia Harbour or Curio Bay. The taxa represented in the collections from each site and their natural affinities are listed below in addition to a list of fossil macroflora previously found at Curio Bay\(^1\). It is evident that the New Zealand Temaikan flora was dominated by Filicopsida and Gymnospermopsida related plants.

Macroflora Taxonomic List (excluding fossil wood) from the Urawitiki Measures, Kawhia Harbour:

- **Kingdom PLANTAE**
  - **Division BRYOPHYTA**
    - **Class ?BRYOPSIDA**
      - *Gen. indet.*
  - **Division TRACHEOPHYTA**
    - **Class FILICOPSIDA**

\(^1\) The Urawitiki Measures plants are previously undescribed.
Continued:

Order FILICALES
Family ?Osmundaceae
Cladophlebis cf. australis
Cladophlebis cf. denticulata
Cladophlebis spp.
?Ashicaulis sp.

Fern Scale  Gen. indet.
Class GYMNOSPERMOPSIDA
Order CONIFERALES
Elatocladus conferta
Seed cone  Gen. indet.
Seed-bearing cone scales  Gen. indet.
Seeds  Gen. indet.
Order CYCADALES
Taeniopteris daintreei

Macroflora Taxonomic List (excluding fossil wood) collected from the Curio Bay region, Southland:

Kingdom PLANTAE
Division TRACHEOPHYTA
Class LYCOPSIDA
Order ?LYCOPODIALES
?Lycopodites sp.

Class SPHENOPSIDA
Order EQUISETALES
Family Equisetaceae
Equisetites hollowayi

Class FILICOPSIDA
Order FILICALES
Family Osmundaceae, Sub-family Osmundoideae
Ashicaulis gibbiana
?Ashicaulis sp.
Family ?Osmundaceae
Cladophlebis sp. ?

Class GYMNOSPERMOPSIDA
Order CONIFERALES
Elatocladus sp.
Order CYCADEOIDALES
Ptilophyllum acutifolium
Additional macroflora (excluding fossil wood) previously described from the Curio Bay region, Southland (Edwards, 1934; Pole, 1988; Raine and Pole, 1988):

Kingdom PLANTAE
Division TRACHEOPHYTA
Class LYCOPSIDA
Order LYCOPODIALES
  Lycodites arberi
Class FILICOPSIDA
Order FILICALES
  Family Dicksoniaceae
    Coniopteris hymenophylloides
  Family Osmundaceae, Sub-family Osmundoideae
    Cladophlebis indica
    Ashicaulis dunlopi
Class GYMNOSPERMOPSIDA
Order CONIFERALES
  Araucarites grandis
  Carpolithus sp.
  Palissya bartumi
  Podozamites gracilis
Order CYCADALES
  Cycadites sp.
  Nilssonia compta
  Taeniopteris vittata
  Taeniopteris spatulata
Order CYCADEOIDEALES
  Otazamites sp.
  Ptilophyllum sp.
  Pterophyllum sp.
4.23 Fossil Wood

Introduction

Silicified wood with well-preserved cellular structure collected from the uppermost Uravitiki Measures in Kawhia Harbour was found either as fossilised tree stumps still in growth position (for example, Figure 1.31), as fossilised trunk portions (for example, Figure 4.210(a)) not in growth position or as loose material amongst the beach pebbles (ex situ, for example, Figure 4.210(b)). Ninety-one specimens originating from the Uravitiki Measures strata were collected. Carbonaceous remnants of other wood fragments occurred scattered throughout the formation as streaks of coal with no preserved cellular structure (Enclosures 1-5). Due to the silicified nature of the ex situ material, the sheltered aspect of the beaches and poor public accessibility it is assumed that the specimens collected were sourced locally.

A small collection of 14 specimens of Temaikan fossil wood was made from a track-side cutting on the cliff-top at Slope Point, west of Curio Bay in Southland (Figure 1.310). Sampling of in situ material from Curio Bay itself is prohibited by the Department of Conservation (Section 1.41). All the fossil wood specimens from both Kawhia Harbour and Slope Point consist of fragments of secondary xylem. Appendix E describes the laboratory methods and includes sample data sheets used in the analysis of the collection.
Figure 4.210 Silicified wood from the uppermost Urawitiki Measures, Kawhia Harbour.
(a) Trunk portion within mapped unit OP16 (Appendix C), Opapaka Point section, Te Maika Peninsula, Kawhia Harbour. Sticker on hammer = 12 cm long.
(b) Fossilised wood sample VH224, Protocupressinoxylon sp. A (p. 212). Ex situ, Totara Peninsula section, Kawhia Harbour. Actual size.
The following section discusses the mode of preservation of the fossil wood collected, the history of fossil wood taxonomic descriptions and the current forms of classification in use. In addition, a brief description of wood histology and the process of fossil conifer wood identification introduces the systematic descriptions.

**Preservation**

The fossil wood collected from the uppermost Urawitiki Measures, Kawhia Harbour and Slope Point is preserved by *cellular permineralisation* in silica. Synonymous with *petrifaction*, this is the most faithful to life of any mode of fossil preservation known (Schopf, 1975). The process involves early permeation of the plant tissues by silica-rich water and subsequent precipitation of colloidal or microcrystalline silica in the interstices. Much of the original organic material remains, but it is embedded in a finely crystalline matrix.

Many of the uppermost Urawitiki Measures specimens had a low proportion of silica compared to organic matter, so that the core was carbonaceous, friable and cellular detail was indiscernible. However, where these specimens were subaerially exposed a thin surface layer (up to approximately 10 cells thick) had effectively become bleached allowing clear observation of the histology under the stereomicroscope (for example, Figure 4.211(a)). A similar mode of preservation was observed within the fossilised tree stumps at Curio Bay in Southland. However, due to the fragmentary nature of specimens preserved in this manner, petrological thin sections could not be taken. Fresh fractured
blocks (~1 cm³) were examined under the Scanning Electron Microscope (S.E.M.) to search for very fine cellular details, for example, the cross-field pitting which is essential for identification to species level (for example, Plate 21, Figures 3,4).

The remainder of specimens from Kawhia Harbour and all the specimens collected at Slope Point contain of a higher proportion of silica to organic matter. These highly silicified specimens are light in colour (the Slope Point specimens are also stained yellow with iron-oxide) and are very hard (for example, Figure 4.211(b)). These specimens could be thin sectioned and fine cellular details were easily observed under a transmitted light microscope (refer to Appendix E for full methods).

The process of fossil forest floor burial, which is considered to have been similar at both the Kawhia Harbour and Curio Bay localities, suggests that mineralisation would have occurred near the surface (Figure 2.231). Most modern examples of near-surface (low temperature) silicification occur in desert environments, aided by intense evaporation and crystallisation from groundwater super-saturated in silica. For example, in the Mundowndna area, south Australia, red and buff silcrete⁠² forms in a combined laterite/silcrete profile (Dickinson, pers. commun., 1998). However, the sedimentology and palaeobotanical evidence from the Urawitiki Measures and sediments in the Curio Bay region imply the climate was humid in the Middle Jurassic in the Murihiku basin, with no shortage of water. The humid palaeoclimate suggests that concentration of

¹ The silica-indurated products of surface and near-surface diagenesis (Summerfield, 1983a,b,c; McBride, 1989).
Figure 4.211 Differing permineralisation modes of fossilised wood fragments, Urawitiki Measures, Te Maika Peninsula, Kawhia Harbour.

(a) Cellular structure only visible on the bleached weathered surface. Specimen has a low proportion of silica to organic matter. Sample VH180, Protocupressinoxylon sp.A (p. 212), Southern Ohanga Bay section.

(b) Cellular structure visible throughout where there is an evenly distributed and high proportion of silica to organic matter. Sample VH188, Podocarpoxylon sp. A (p. 219), Jetty section.
dissolved silica in the groundwater was unlikely to be a result of evaporation. The source of the silica could well have been the volcaniclastic component of the Murihiku sediments derived from arc mountains along the Gondwanaland margin.

A further example of near-surface silicification occurs in the Miocene of Landslip Hill, Otago, South Island, New Zealand (Lindqvist, 1990). Silicified plant remains are found in silcretes at this locality where it is thought silicification occurred due to the interaction of silica-saturated groundwater and organic compounds derived from abundant plant matter. This suggests that near-surface silicification could occur in a humid, vegetated environment, where silica would be easily transported in solution. A situation similar to this could well have occurred during deposition and burial of the Temaikan forest floors.

*The Classification of Fossil Conifer Woods*

Literature on the taxonomic classification of fossilised coniferous woods is in a fragmentary state with many authors, mainly since the late 1800’s, publishing observations and naming new species without an easy method of cross-referencing those already in existence. Furthermore, no standard rules for the diagnosis of new species have been established and different authors differentiate new taxa on the basis of cellular features considered unsuitable by others and so the controversy continues.
Fossil wood was first described as *Lithoxylon* by Luidius in 1699. The suffix *-xylon* is still used in generic nomenclature. Various prefixes are attached which imply similar characteristics to a recent genus or family (for example, *Cedroxylon* Kraus) or which describe diagnostic anatomical characteristics (for example, *Circoporoxylon* Kräusel, meaning "round pores"). A long list of form genera now exist (see for example, Kräusel, 1949; Stewart and Rothwell, 1993) and more recently their natural affinities have begun to be investigated (Vogellehner, 1967, 1968). This is a difficult task as many of the geologically older fossils exhibit characteristics that do not compare with extant genera and probably represent their primitive ancestors. In addition, it is rare to find coniferous vegetative or reproductive structures (from which natural affinities are more easily determined) in organic connection with fragments of secondary wood (Stewart and Rothwell, 1993).

Nicol (1834) and Witham used thin section cutting methods in their first scientific investigation of fossilised wood. Since that time more knowledge has been gained about the detailed structure and the taxonomic value of certain characteristics has changed. Investigations of extant secondary wood now examine the *ultrastructure* of cell walls (Côte, 1965), but the taxonomic value of such a technique in the fossil record, especially as far back as the Mesozoic, is restricted by incomplete preservation.

Today, fossilised wood is classified by either: (1) the normal Linnean classification system or (2) the Palaeontologic Data-Handling System (P.D.H.S.) (Hughes and Moody-}

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1 Bibliographic reference not found.
Stuart, 1969; Hughes, 1989; discussed in Chapman and Smellie, 1992). Most authors still favour the Linnean system. However, the P.D.H.S. is useful for comparing fossilised wood samples that lack the fine cellular details required by Linnean taxonomic keys (for example, Kräusel, 1949), is effective for the detailed recording of limited amounts of material and avoids inadequate taxa being entered into the taxonomic literature. Unfortunately, the P.D.H.S. has not been widely accepted (Chapman and Smellie 1992). The fossil wood systematics in the following section are classified using the Linnean system for ease of comparison to previously described fossil wood, to maintain a consistent mode of classification throughout the various fossil plant organs in this study and to aid vegetation reconstruction using the implied natural affinities.

The Histology of Gymnospermous Wood and Annual Growth Rings

Detailed cellular features are essential for the adequate description and classification of fossil wood. Figure 4.212 provides a visual glossary of terms used in the following systematic descriptions, with reference to three oriented sections of the secondary xylem: transverse, radial longitudinal and tangential longitudinal. For a complete description of gymnospermous wood histology the reader is referred to Jane (1970).

Growth rings are clearly visible in the transverse and often the radial longitudinal sections of a stem (Figure 4.212) and occur within all the specimens studied from Kawhia Harbour and Slope Point. They are formed by the varying diameters and wall
Figure 4.212 Gross wood morphology, sections viewed and histological terms used in systematic descriptions. For complete description see Jane, 1970. X: transverse, R = longitudinal radial, T: longitudinal tangential sections.
(a) earlywood, (b) latewood, (c) ring boundary, (d) ray parenchyma, (d(i)) uniseriate ray, (d(ii)) biseriate ray, (e) axial parenchyma, (f) tracheid, (g) middle lamella, (h) lumen, (i) primary and (j) secondary cell walls, (k) tangential tracheid pitting, (l) tapering tracheid end walls, (m) axial parenchyma end walls, (n) checking, (o) spiral thickening, (p) biseriate, opposite, bordered tracheid pitting, (q) biseriate, alternate, bordered tracheid pitting, (r) *araucarioid* tracheid pitting, (s) uniseriate bordered tracheid pitting, (t) contiguous pitting, (u) separate pitting, (v) crassulae, (w) simple cross-field pitting, (x) ray cell end walls.
thickness of tracheid cells, which constitute the majority of the secondary xylem (Figure 4.213). In the following systematic descriptions, cellular dimensions are averaged from samples of 25 undistorted cells. At the beginning of Spring, relatively large, often hexagonal, thin-walled tracheids are formed, termed the earlywood (EW). Towards the end of the growing season, the cells commonly become radially flattened, rectangular in shape and the cell walls tend to thicken creating latewood (LW) cells. The transition between the two may be gradual, but can also be abrupt and the proportion of LW varies throughout the tree and between taxa. The transitions between EW and LW is commonly difficult to determine over gradual boundaries by simple observation (either in hand specimen or thin-section). A method for distinguishing the two cell types using measurements of the tracheid radial diameters is discussed in Section 5.3.

Irregularities within growth rings include false rings which are zones of smaller cells that may form, within the main ring, usually due to a period of drought within the growing season. Frost rings may also occur as a zone of damaged cells which can be caused by insect attack or fire as well as frost events. Resin may also be present within tracheid or parenchyma cell lumina or as resin canals, oriented either axially or radially within the medullary rays.
Figure 4.213  The form of annual growth rings.
(a)  An annual growth ring to indicate the varying diameter and wall thickness of tracheid cells between ring boundaries. The centre of the stem is located to the left. Modified from Creber and Chaloner, 1984b.
(b)  An annual growth ring from sample VH189, Urawitiki Measures, Kawhia Harbour. Ring width = 1.9 mm.

EW = earlywood cells (Spring growth), LW = latewood cells (Summer growth), RB = ring boundary.
Identifying Fossil Conifer Wood

The process of studying and subsequently classifying a specimen of fossilised wood is notoriously difficult. The problems occur due to the necessity for a very specialised knowledge of the structure and variability of cellular characteristics not only within a single species, but also within a single stem. The mode and quality of preservation further limits observation of detailed cellular features. For example, the dimensions of cells and cell walls, the density of elements, or the absence of a character may be the result of alteration and fossilisation processes and do not reflect the original morphology of the living tree.

Many problems with the comparison of new specimens with species previously described occur due to differing opinions on the relative taxonomic importance assigned to each cellular characteristic. For example, Figure 4.214 illustrates that the nature of growth rings, size and number of tracheids and the presence or absence of axial parenchyma varies so significantly throughout a tree that their use for taxonomic division at all is questionable. A standard format of description is required so that cellular features can be designated of taxonomic significance or not, resulting in a more meaningful comparison.

Table 4.3 lists cellular characteristics that are considered taxonomically diagnostic by the author which vary insignificantly throughout the tree, species or as a result of environmental variables. Table 4.4 lists additional features included in most
descriptions of fossilised wood specimens which should be used with caution due to a tendency for marked variation. For example, the features of growth rings within a specimen should not be used for taxonomic descriptions due to the influence of the external environment on their form. However, they should be used to estimate the original locality of the specimen within the stem radius (derived from the ring curvature).

Figure 4.214 Growth ring characteristics of recent twig, branch, trunk, stump and root wood. After Chapman, 1994.

and overall position within the entire tree (Figure 4.214) if this was not possible during collection. This information allows a more accurate comparison between specimens identified as having originated from a similar location within a tree which is often not stated in fossil wood descriptions. Further, cellular features that are known to vary with
position in the tree, for example, medullary ray height (Table 4.4), can then be used for comparison. Therefore, cellular features that are determined to be variable in general may not be entirely precluded from the taxonomic description of certain specimens. Further, on microscopic examination the form and arrangement of the cells can determine whether the specimen represents reaction or injured wood which decides the suitability of intercellular spaces, axial parenchyma and resin canals for taxonomic description.

Tables 4.3 and 4.4 are based on cellular features commonly described from fossilised woods of gymnospermous affinity and are not exhaustive lists. Many especially diagnostic features, for example, septate tracheids, allow immediate comparison with a range of previously described woods.

_Fossil Wood Species Comparative Data Set_

The difficulty of recognising direct botanical affinities between Mesozoic fossilised woods and extant relatives requires classification into form genera. The cellular structure of the majority of specimens from both Kawhia Harbour and Slope Point described in the following section (except samples VH197 and VH263-266) can be compared to the general histology of several fossil wood form genera: _Circoporoxyylon_ Kräusel, 1949; _Mesembrioxyylon_ Seward, 1919; _Phyllocladoxyylon_ Gothan, 1905;

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1 Cellular form and arrangement is different compared to wood during normal growth (refer to Jane, 1970 for further information).
Podocarpxylon (Gothan) *emend.* Stopes, 1915 and also two transitional forms: *Protocupressinoxylon* Eckhold, 1922 and *Protopodocarpxylon* Eckhold, 1922. Previously described Mesozoic species within these form genera from both Gondwanaland and Laurasia origins are compared with the Kawhia Harbour and Curio Bay specimens (Tables F1, F2 and F3, Appendix F).

**Table 4.3** Diagnostic cellular characteristics of fossilised wood.

<table>
<thead>
<tr>
<th>Diagnostic cellular characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form, size and distribution of cross-field pitting</td>
</tr>
<tr>
<td>Pitting of medullary ray cell end (tangential) and horizontal (transverse) walls</td>
</tr>
<tr>
<td>Seriality of medullary rays</td>
</tr>
<tr>
<td>Seriality, shape, separation and arrangement of radial tracheid bordered pitting</td>
</tr>
<tr>
<td>Presence/absence and nature of tangential tracheid pitting</td>
</tr>
<tr>
<td>Presence/absence septate tracheids</td>
</tr>
</tbody>
</table>

**Table 4.4** Cellular characteristics subject to variation within the tree or due to environmental factors.

<table>
<thead>
<tr>
<th>Cellular characteristics</th>
<th>Cause of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth ring features (including distinctiveness, width, EW-LW transition, relative amounts of EW and LW, false and frost rings)</td>
<td>Climate (including seasonality, water supply, temperature, rapidity of season change, fire, insect damage), position within tree and stem radius (Figure 4.214).</td>
</tr>
<tr>
<td>Medullary ray height(^1) and density; medullary ray parenchyma and tracheid cell size; pit sizes.</td>
<td>Younger woods have lower medullary rays, higher medullary ray density and smaller cells and pits.</td>
</tr>
<tr>
<td>Intercellular spaces</td>
<td>May be reaction wood.</td>
</tr>
<tr>
<td>Axial parenchyma and resin canals (including presence/absence, abundance, occurrence within growth ring)</td>
<td>May be result of trauma (usually injury).</td>
</tr>
<tr>
<td>Presence/absence crassulae</td>
<td>Inconsistent appearance in extant trees of same species.</td>
</tr>
</tbody>
</table>

\(^1\) Refers to the appearance of medullary rays in tangential section (Figure 4.212) – often quantified by quoting a range and average number of cells.
Systematic Descriptions

DIVISION TRACHEOPHYTA
CLASS GYMNOSPERMOPSIDA
ORDER CONIFERALES
FAMILY ARAUCARIACEAE
FORM GENUS Araucarioxyylon Kraus 1872

Form genus diagnosis (Seward, 1919):
Bordered pits on radial tracheid wall. Contiguous and slightly flattened if uniseriate, alternate and polygonal when biseriate or multiseriate. Rarely separate and circular. Crassulae usually absent. Axial parenchyma absent or rare. Medullary rays uniseriate, rarely biseriate. Horizontal and tangential medullary ray parenchyma walls smooth. 1-15 small, simple or bordered, circular or elliptical pits per cross-field. Resin canals absent.

Araucarioxyylon sp. A
Plate 9, Figures 1-8.

Sample numbers: VH263-266 (plus thin sections: VH263 A,B; VH264 A-C; VH265 A-C; VH266 A); ex situ samples.
Histology and description:

All four specimens assigned to the *Araucarioxylon* sp. A morphotype originated from various positions within the radii of trunks or stumps. The majority of the specimens show some degree of pre-silicification distortion.

Distinct growth rings with an apparently narrow LW zone (typically 3-6 cells) (Plate 9, Figure 1). EW to LW transition is gradual. No false or frost rings. Tracheids arranged in closely packed, regular radial files with no intercellular spaces. EW tracheids polygonal and commonly radially elongate in cross-section, flattening tangentially to become quadrangular in the LW. Tracheids maintain a similar diameter throughout their length. Tracheid end walls are not observed. Rare axial parenchyma plugged with resin (Plate 9, Figure 2) and scattered throughout the growth rings. In radial section, axial parenchyma cells are elongate and oblong in shape, with smooth, horizontal end walls. No resin canals. Table 4.5 presents the cross-sectional dimensions of the tracheid cells.

Cell wall thickness is relatively constant within each cell.

Tracheid radial wall bordered pits numerous and elliptical with circular or inclined elliptical (at ~45°) apertures (average pit diameter = 12.7 μm; average pit aperture diameter = 3.7 μm) (Plate 9, Figure 3). Pit diameter is relatively constant and extends over ~100% of individual tracheids. Uniseriate, rarely biseriate-alternate in the wider tracheids (Plate 9, Figure 4). Pits are predominantly contiguous and vertically flattened,

1 Pit and aperture dimensions are averaged from a sample of 15 pits from several tracheids. This method was applied to all the fossil wood specimens studied.
but very rarely separate. No crassulae. Tracheid tangential wall pitting is not observed.

Table 4.5  *Araucarioxylon* sp. A tracheid overall size, cell wall and cell lumen dimensions (μm).

<table>
<thead>
<tr>
<th></th>
<th>EW</th>
<th>LW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radial dimension</td>
<td>51.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Average tangential dimension</td>
<td>32.6</td>
<td>36.0</td>
</tr>
<tr>
<td>Radial cell wall thickness (min) mean (max)</td>
<td>(3.3) 3.7 (5.1)</td>
<td>(5.2) 6.7 (8.6)</td>
</tr>
<tr>
<td>Radial cell lumen diameter (min) mean (max)</td>
<td>(24.0) 39.8 (48.0)</td>
<td>(10.3) 15.8 (20.6)</td>
</tr>
<tr>
<td>Average cell wall:lumen ratio</td>
<td>1:10.9</td>
<td>1:3.8</td>
</tr>
</tbody>
</table>

Medullary rays cross ring boundaries in the transverse section and are spaced at an average of 5 tracheids distant¹ (between 1 and 10 tracheids) (Plate 9, Figure 1). Medullary rays appear numerous in transverse section. Wholly parenchymatous. Uniseriate. Height range = 2-31 (mostly 7-9) cells. In tangential section, medullary ray cells approximately circular and generally isodiametric (Plate 9, Figure 5). In radial section, medullary ray cells span 1.5-5 tracheids (Plate 9, Figure 6). Horizontal and tangential walls smooth. The tangential walls are predominantly vertical, but rarely oblique. Up to 6 (mainly 2-4) pits per cross-field, either oblique, slit-like apertures or open and circular to slightly oblique apertures (average pit diameter = 5.1 μm) (Plate 9, Figures 7,8). Pits arranged vertically or obliquely.

¹ Medullary ray spacing and heights are determined by thin-section observation and stereomicroscopy using hand specimens. Medullary ray spacing is averaged from 15 medullary rays within one growth ring. Medullary ray heights are averaged from a sample of 25 medullary rays from each specimen. These methods were applied to all the fossil wood specimens studied.
Remarks:

Fossil wood with the characteristic *araucarioid* radial bordered pitting (Figure 4.212) has previously been assigned to either *Dadoxylon* Endlicher 1847a or *Araucarioxylon* Kraus 1872. Jeyasingh and Kumarasamy (1995) summarise usage of these two genera and conclude that *Araucarioxylon* is used generally for *Mesozoic* woods with *araucarioid* pitting, mainly uniseriate medullary rays and for specimens with no information available about the pith and primary xylem. Therefore, *Araucarioxylon* is considered the most appropriate nomenclature for samples VH263-266. Consistent details of the medullary rays and cross-field pitting between specimens assigned to *Araucarioxylon* sp. allow this informal designation.

Middle Jurassic *Araucarioxylon*-type wood has previously been described from the Curio Bay fossil forest deposits in Southland (Edwards, 1934) and identified as *Dadoxylon australe* (Crié) Edwards, 1934. Samples VH263-266 differ from this species in the predominantly uniseriate tracheid radial wall bordered pitting, the less numerous (and simple) pits per cross-field, the rare presence of axial parenchyma and the occurrence of significantly higher rays (Edwards (1934) noted ray heights of 1-15 cells in *Dadoxylon australe* (Crié) Edwards, 1934).

Further *Araucarioxylon*-type wood has been described from Amuri Bluff in the mid-Cretaceous of New Zealand by Stopes (1916). However, *Araucarioxylon novae* 1

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1 Hereafter referred to as *Dadoxylon* following the original description but, following the discussion on nomenclature, should be re-combined as *Araucarioxylon* in a future publication.

2 *Dadoxylon australe* Crié 1888 has multiseriate (1-3 rows, rarely 4) tracheid radial wall bordered pits.
zeelandii Stopes, 1916 has predominantly biseriate, alternate tracheid radial bordered pitting and distinctive resin spools developed in several tracheids parallel to the medullary rays, so cannot be compared to the Slope Point specimens.

Known New Zealand Jurassic Occurrence:

Middle Jurassic: Slope Point, Southland (this thesis).

_Araucarioxylon_ sp.

Plate 10, Figures 1-3; Plate 11, Figure 1.

Sample numbers: VH197 (plus thin sections: VH197A-F); _ex situ_ sample.

Histology and Description:

Cubic, _ex situ_ specimen measuring 5.0 x 3.5 x 4.5 cm. The sample is a light brown/grey colour, is well-silicified, but has patchy preservation. Growth rings are distinct and visible on both transverse (Plate 10, Figures 1-3) and radial longitudinal sections. There are no false or frost rings. Each ring has a narrow LW zone (average 15 cells) and a wide, mainly distorted EW zone. There is a gradual EW to LW transition. Straight ring boundaries indicate the sample originated from the outer trunk region. Rings are entirely composed of tracheid cells with no axial parenchyma.

Tracheid cells are arranged in closely packed, regular radial files with no intercellular spaces (Plate 10, Figures 2,3). Undistorted tracheids are mainly circular in cross-section
with LW cells becoming tangentially flattened towards the ring boundary. Tracheid length in radial section is indeterminate due to preservation, but they maintain a consistent diameter throughout. Tracheid end walls taper. Table 4.6 presents the cross-sectional dimensions of the LW tracheids. EW tracheids are too distorted for measurement. Cell wall thickness remains relatively constant within each cell. Many EW cells are infilled with resin, but the LW cell lumina remained empty prior to silicification (Plate 10, Figure 3).

Tracheid radial walls exhibit contiguous bordered pits, either uniseriate (circular or vertically flattened) or frequently biseriate (hexagonal) with an alternate arrangement (generally in the wider tracheids) (Plate 11, Figure 1). Pit apertures are not visible.

Table 4.6  *Araucarioxylon* sp. LW tracheid cell overall size, cell wall and cell lumen dimensions (µm). EW cells too distorted for measurement.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radial dimension</td>
<td>26.9</td>
</tr>
<tr>
<td>Average tangential dimension</td>
<td>30.8</td>
</tr>
<tr>
<td>Radial cell wall thickness (min) mean (max)</td>
<td>(3.5) 4.9 (8.6)</td>
</tr>
<tr>
<td>Radial cell lumen diameter (min) mean (max)</td>
<td>(5.2) 15.7 (24.2)</td>
</tr>
<tr>
<td>Average cell wall:lumen ratio</td>
<td>1:3.2</td>
</tr>
</tbody>
</table>

Medullary rays are represented by irregularly spaced, radially aligned cracks, filled with microcrystalline quartz and flecks of organic matter, but with no cellular structure (Plate 10, Figures 2,3). The medullary ray infilled cracks are radially extensive (passing through ring boundaries), occur at an average spacing of 8 tracheid cells and appear of uniseriate width in transverse section. The medullary ray height is estimated to be 1-19
cells, but mostly 4-10 cells. No cross-field pitting or tangential section details are preserved.

**Remarks:**

*Araucarioxylon* is considered the most appropriate nomenclature for sample VH197 (refer to the *Remarks* for *Araucarioxylon* sp. A, p. 208). However, due to incomplete preservation, separate species designation is not possible. This specimen differs from the Slope Point specimens in the predominantly biseriate, *araucarioid* tracheid radial wall bordered pitting and lack of medullary ray or cross-field pitting details. *Araucarioxylon novae zeelandii* Stopes, 1916 has biseriate-alternate tracheid radial wall bordered pitting similar to sample VH197. However, a comparison is not possible due to distinctive resin spools developed in several tracheids parallel to the medullary rays in the former taxon and lack of cellular detail in sample VH197.

**Known New Zealand Jurassic Occurrence:**

Middle Jurassic: Totara Peninsula section, Kawhia Regional Syncline (this thesis).
FAMILY CUPRESSACEAE

FORM GENUS Protocupressinoxylon Eckhold, 1922

Form genus diagnosis (from Kräusel, 1949):

Gymnospermous wood with bordered pits on tracheid radial walls arranged as in transitional forms (both separate and contiguous). Cross-field pitting is cupressoid. Medullary ray cell walls are mostly smooth and axial parenchyma is either present (and may be abundant) or absent.

Protocupressinoxylon sp. A

Plate 11, Figure 2; Plate 12, Figures 1-6; Plate 13, Figures 1-4;
Plate 14, Figures 1-5; Plate 15, Figures 1-5.


Histology:

Distinct growth rings with a narrow LW zone (typically 4-5 cells) (Plate 13, Figures 1-

---

1 Small, bordered, or partially bordered pits with a fairly elliptical, wide aperture which is included, but which may extend to the border along its long axis (Jane, 1970).
4). EW to LW transition is gradual. No false or frost rings. Tracheids arranged in closely packed, regular radial files with no intercellular spaces (Plate 14, Figure 1). EW tracheids circular to polygonal and commonly radially elongate in cross-section, flattening tangentially to become quadrangular in the LW. Tracheids maintain a similar diameter throughout their length. Tracheid end walls are not observed. Abundant axial parenchyma often plugged with resin and scattered throughout the growth rings (Plate 15, Figure 1). In radial and tangential section, axial parenchyma cells are elongate and oblong in shape, with smooth, horizontal end walls. No resin canals. Table 4.7 presents the cross-sectional dimensions of the tracheid cells. Cell wall thickness is relatively constant within each cell.

Table 4.7  *Protocupressinoxylon* sp. A tracheid overall size, cell wall and cell lumen dimensions (µm).

<table>
<thead>
<tr>
<th></th>
<th><em>EW</em></th>
<th><em>LW</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radial dimension</td>
<td>38.7</td>
<td>16.6</td>
</tr>
<tr>
<td>Average tangential dimension</td>
<td>30.0</td>
<td>27.8</td>
</tr>
<tr>
<td>Radial cell wall thickness (min) mean (max)</td>
<td>(1.8) 2.7 (3.5)</td>
<td>(3.5) 5.2 (7.0)</td>
</tr>
<tr>
<td>Radial cell lumen diameter (min) mean (max)</td>
<td>(24.3) 33.9 (45.3)</td>
<td>(5.2) 10.4 (15.7)</td>
</tr>
<tr>
<td>Average cell wall:lumen ratio</td>
<td>1:13.6</td>
<td>1:2.3</td>
</tr>
</tbody>
</table>

Tracheid radial wall pits numerous, circular or elliptical with circular apertures (average pit diameter = 14.5 µm; average pit aperture diameter = 3.5 µm) (Plate 14, Figures 2,4,5). Pit diameter is relatively constant and extends over ~50-90% of individual
tracheids. Uniseriate. Pits are separate, but generally closely spaced and occasionally contiguous (but not vertically flattened). No crassulae. Tracheid tangential wall pitting is common and not restricted to the LW (Plate 15, Figure 2). Tangential pits slightly smaller than the radial wall pits with an indistinct border, uniseriate, both separate and contiguous (but not vertically flattened).

Medullary rays cross ring boundaries in the transverse section and are spaced at an average of 7 tracheids distant (between 1 and 13 tracheids) (Plate 13, Figures 1-4). Medullary rays appear numerous in transverse section. Wholly parenchymatous. Uniseriate. Height range = 1-8 (mostly 2) cells (Plate 15, Figures 1,3-5). In tangential section, medullary ray cells elliptical and vertically elongate with marginal cells slightly tapering. Medullary ray cells also generally isodiametric in tangential section. In radial section, medullary ray cells span 2-8 tracheids (Plate 14, Figures 2,3). Horizontal and tangential walls smooth and thick (~2.5 µm). The tangential walls are vertical and rounded. 1 (rarely 3-4) pits per cross-field (average pit diameter = 9.2 µm) (Plate 14, Figure 2). Single pits cover ~40% of the cross-field. Circular and simple with apparently dentate margins due to adherent fine resiniferous granules. When two pits in the cross-field, arranged obliquely. Preservation of cross-field pits generally poor.

**Description:**

A total of 36 specimens collected from fossilised tree stumps and loose beach debris on Te Maika and Totara Peninsulas, Kawhia Harbour, are included in this description. Blocks of in-growth-position and *ex situ* material, up to a maximum dimension of 14.5
cm, are generally fractured along radial or tangential surfaces (Plate 12, Figures 4-6). All specimens originated from various positions within the radii of trunks or stumps. The majority of the in-growth-position and all of the ex situ specimens show only minimal cellular distortion.

Several specimens provide information about the life habits of the trees. Sample VH245 exhibits extremely well preserved cellular structure including distinct undistorted growth rings and evidence of gross structure in the form of well-developed knots representing the site of attachment of annularly arranged branches (Plate 12, Figures 1-3). In addition, sample VH228 represents a silicified decorticated stem filled with fragments of secondary xylem and adventitious rootlets prior to fossilisation. The rootlets contain a small stele (Plate 11, Figure 2) which is characteristic of extant plants with submerged roots (Neushul, 1974). This morphology provides palaeobotanical evidence for a humid climate and a high water table in the region of the Urawitiki Measures forests.

Variation of fine cellular details between the specimens is difficult to determine due to differing amounts of distortion and preservation and only the best preserved samples were thin-sectioned. Table F4 (Appendix F) presents variation in the nature of medullary rays as observed in thin-section and hand specimen. The number of biseriate medullary rays observed was counted over as wide an area as preservation allowed. Overall, no biseriate medullary rays were observed in any of the specimens. Ray height varies little from 1-10 cells, with most generally very low (2-5 cells). A measure of the standard deviation of medullary ray height within each specimen provided a measure of
overall medullary ray height range. The standard deviations for the samples of this morphotype are all <2.0 cells, indicating the range of medullary ray heights was also low within each specimen.

Remarks:
The distinguishing features of the fossil wood material described above are the numerous and mainly separate, but closely spaced, uniseriate bordered pitting on the tracheid radial walls; the small, predominantly single, circular, dentate-marginated cross-field pits; the tracheid tangential wall pitting and the wholly uniseriate nature of the medullary rays. In addition, the especially low medullary rays with low height variation within each specimen and the abundance of axial parenchyma are distinctive features. As previously discussed, the occurrence of axial parenchyma and medullary ray height are not considered diagnostic cellular characteristics in general (p. 201; Table 4.4). Firstly, it is unlikely that the abundant axial parenchyma is traumatic due to its consistent occurrence throughout the specimens examined¹. Secondly, all the specimens originated from a similar location within a tree (the trunk or stump), but from varying positions within the radius. Regardless of stem age, all showed the characteristic low medullary ray height and low medullary ray height range. Therefore, axial parenchyma and medullary ray height are valid diagnostic features for this material.

Fossil wood named Cretaceous-spacedpits from the Upper Cretaceous of Antarctica (Table F2, Appendix F) has similar cellular morphology to the material described, but

¹ Axial parenchyma could only be observed in the samples that were thin-sectioned.
has large cross-field pits and a very large medullary ray height range and cannot be
directly compared (Chapman and Smellie, 1992). From the Mesozoic of Laurasia (Table
F3, Appendix F), Protocupressinoxylon Solmsi (Stopes) Kräusel, 1949 and
Protocupressinoxylon vectense (Barber) Kräusel, 1949 from Cretaceous strata on the Isle
of Wight, U.K., are closest in structure and have abundant, resiniferous axial
parenchyma, especially low medullary rays and tracheid tangential wall pitting.
However, cross-field pitting is not preserved in Protocupressinoxylon Solmsi (Stopes)
Kräusel, 1949, so the Urawitiki Measures material cannot be directly compared to this
taxon. Protocupressinoxylon vectense (Barber) Kräusel, 1949 has similar cross-field
pitting, but has rare biseriate opposite tracheid radial wall pitting and rare biseriate
medullary rays which were not observed in the Urawitiki Measures material. Therefore,
direct comparison is not possible with any previously described fossil wood taxa from
the Mesozoic of Gondwanaland or Laurasia (Tables F2 and F3, Appendix F).

Known New Zealand Jurassic Occurrence:

Middle Jurassic: Opapaka Point and Ohanga Bay sections, Te Maika Peninsula; Totara
Peninsula section, Kawhia Regional Syncline (this thesis).
FAMILY PODOCARPACEAE

FORM GENUS Podocarpoxyylon Gothan emend. Stopes, 1915

*Form genus diagnosis* (Stopes, 1915):
Gymnospermous wood with no resin canals. Tracheid bordered pits: round, generally separate, uniseriate; if biseriate, opposite and not hexagonally compressed. Medullary rays uniseriate. Abietinean\(^1\) pitting typically absent. Cross-field pits: commonly 1-2, very large, simple or bordered pits per field. Podocarpoid\(^2\) pitting common in latewood. Axial parenchyma present, sometimes abundant.

*Form genus nomenclature:*
Fossil wood with the cellular characteristics listed above are assigned to the form genera *Podocarpoxyylon* Gothan emend. Stopes, 1915 or *Mesembrhinoxylon* Gothan emend. Seward, 1919. Gothan’s (1905) original diagnosis for *Podocarpoxyylon* was altered to allow inclusion of specimens formerly classified as *Phyllocladoxylon* and *Paraphyllocladoxylon* (Stopes, 1915; Seward, 1919). The *Podocarpoxyylon* form genus was then renamed *Mesembrhinoxylon* to remove any implied affinity with the structure of extant *Podocarpus* genus wood (Seward, 1919). There remains disagreement over the nomenclature of the form genus with both still in use. The following Urawitiki Measures material is assigned to *Podocarpoxyylon* Gothan emend. Stopes, 1915 based on the author’s opinion that there is an overall similarity in wood structure between the

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\(^1\) Dense pitting in the horizontal and tangential walls of medullary ray parenchyma cells.

\(^2\) Bordered, small, vertically or steeply inclined oval pores (Seward, 1919).
Mesozoic fossil wood and extant podocarp s. Further, this implied affinity to modern taxa, although it cannot be directly proven or disproven, is useful in the reconstruction of the Urawitiki Measures vegetation community.

**Podocarpoxy l on sp. A**

Plate 16, Figures 1-5; Plate 17, Figures 1-4; Plate 18, Figures 1-3; Plate 19, Figures 1-4; Plate 20, Figures 1-7; Plate 21, Figures 1-4; Plate 22, Figures 1-5.

*Sample numbers:* VH125-128, VH168-173, VH187, VH188, VH221-223; (in-growth-position fossil stump samples). VH189, VH190, VH206-220, VH267-269; *ex situ* samples. Plus S.E.M. mounted fragments: VH125, VH126, VH128, VH169, VH170, VH172, VH188, VH221, VH222 and thin sections: VH188A-F, VH189A-G, VH267A,B, VH268A-C, VH269A-C.

*Histology:*

Distinct growth rings with a narrow LW zone (typically 1-5 cells) (Plate 17, Figures 1-4; Plate 19, Figure 1). EW to LW transition is gradual. No false or frost rings. Tracheids arranged in closely packed, regular radial files with no intercellular spaces (Plate 18, Figure 1). EW tracheids circular to polygonal and radially elongate in cross-section, flattening tangentially to become quadrangular in the LW. Tracheids maintain a similar diameter throughout their length and terminate with tapering, smooth, end walls (Plate 19, Figure 4). Sparse axial parenchyma loosely infilled with resiniferous granules is
scattered throughout the growth ring (Plate 18, Figure 2). In radial and tangential section, parenchyma cells are elongate and oblong in shape, with smooth, horizontal end walls (Plate 20, Figure 2; Plate 22, Figure 2). No resin canals. Table 4.8 presents the cross-sectional dimensions of the tracheid cells. Cell wall thickness is relatively constant within each cell.

**Table 4.8** *Podocarpoxyylon* sp. A tracheid overall size, cell wall and cell lumen dimensions (µm).

<table>
<thead>
<tr>
<th></th>
<th><em>EW</em></th>
<th><em>LW</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radial dimension</td>
<td>31.8</td>
<td>12.8</td>
</tr>
<tr>
<td>Average tangential dimension</td>
<td>19.8</td>
<td>20.8</td>
</tr>
<tr>
<td>Radial cell wall thickness (min) mean (max)</td>
<td>(1.4) 3.1 (4.9)</td>
<td>(2.8) 3.8 (5.6)</td>
</tr>
<tr>
<td>Radial cell lumen diameter (min) mean (max)</td>
<td>(9.8) 23.4 (32.2)</td>
<td>(2.1) 7.1 (11.2)</td>
</tr>
<tr>
<td>Average cell wall:lumen ratio</td>
<td>1:9.0</td>
<td>1:1.9</td>
</tr>
</tbody>
</table>

Border and aperture of tracheid radial wall pits circular (average pit diameter = 15.6 µm; average pit aperture diameter = 3.6 µm) (Plate 19, Figures 2-4; Plate 20, Figures 1-4,6). Pit diameter extends over ~50% of the tracheid width. Uniseriate, very rarely biseriate-opposite. Pits are mainly separate, but occasionally contiguous with slightly vertically flattened pits (Plate 19, Figure 3; Plate 20, Figure 3). Pit separation is variable and can be closely spaced or several pit diameters apart (maximum observed = 11 pit diameters) (Plate 20, Figures 1,2). No crassulae. No tracheid tangential wall pitting.
Medullary rays appear numerous and cross ring boundaries in the transverse section (Plate 17, Figures 1-4). They are irregularly spaced at an average of 6 tracheids apart. Wholly parenchymatous. Uniseriate, very rarely biseriate (Plate 22, Figure 1). Height range = 2-22 (mostly 2-5) cells high (Plate 22, Figures 1-5). In tangential section, medullary ray cells circular with marginal cells slightly elongate. Medullary ray cells also generally isodiametric but can vary within each medullary ray. Granular resin commonly lines walls (Plate 22, Figure 2). In radial section, medullary ray cells span 1-6 tracheids (Plate 21, Figure 1). Horizontal and tangential walls smooth, latter vertical and rounded. 1-2 (rarely 3 or 4) pits per cross-field (average pit diameter = 7.4 μm) (Plate 20, Figures 4-7; Plate 21, Figures 1-4). Each pit covers 20% of the cross-field. Circular or elliptical inclined at a constant angle of 45°; simple or with very narrow dentate margin due to adherent fine resiniferous granules¹ (Plate 20, Figure 7; Plate 21, Figures 1,2). Pit arrangement in field varies: when a single pit, generally at centre of cross-field; when pairs, arranged either horizontally adjacent, vertically adjacent or obliquely.

Description:

A total of 32 specimens collected from fossilised tree stumps and loose beach debris on Te Maika and Totara Peninsulas, Kawkia Harbour and three ex situ specimens from Slope Point, Southland are included in this description. Both in-growth-position and ex situ hand specimens are irregularly shaped blocks, up to a maximum dimension of 7.5 cm. The Urawitiki Measures specimens are generally fractured along radial or tangential

¹ Similar to Protocupressinoso xylon sp. A.
surfaces (Plate 16, Figures 1-4). All specimens originated from various positions within the radii of trunks or stumps. Most specimens show minimal cellular distortion.

Additional information about the growing environment and palaeoecology is provided by certain specimens from the Urawitiki Measures. For example, samples VH209, VH214 and VH218 are further examples of decorticated stems containing floating roots (refer also to p. 215). These rootlet cross-sections have a structure similar to those with a lacunar cortex which consists of cortex strands separating large air spaces radiating from a small stele in the centre (Plate 16, Figure 5). This morphology resembles those of other fossil plants which are interpreted to have grown with their bases submerged in water. For example, the radiating cortex strands are similar to the internal root structure of a Palaeozoic Calamites sp. (a gigantic horsetail) plant with large air spaces (lacunae) in the cortex adapted for wet growing conditions (Stopes, 1910). In samples VH209, VH214 and VH218, these lacunae are filled with large pith cells which could well have had a similar function. This root morphology is evidence of a humid climate and wet substrate. In addition, within a tracheid lumen of sample VH189, a fungal hyphae is present indicating the onset of decomposition (Plate 20, Figure 4) and sample VH219 contains a wood knot which represents the site of branch attachment to the main stem.

Many of the 32 samples have tracheid cells which exhibit post-mortem, but presilicification, modification of the cellular structure. For example, in transverse sections of samples VH188 and VH269, many EW tracheids show prominent separation of the secondary cell wall from the primary cell wall and middle lamella (Plate 18, Figure 3).
This separation of tracheid cell walls is evidence for the rapid silicification after burial. The middle lamella (Figure 4.212) and living cell contents are the first parts of the secondary wood to decay, commonly leaving an empty void between and within cells prior to fossilisation (Leo and Barghoorn, 1976). These voids act as a transport mechanism for siliceous fluids which subsequently fill and crystallise within the gaps. Degradation then begins in the S2 layer of the secondary cell wall, which is the thickest, but least resistant of all the cell wall layers. The thick wall floating in the tracheid could well represent this layer suggesting that little decay occurred prior to silicification. The proposed mechanism of uppermost Urawitiki Measures forest burial (Figure 2.231) suggests that during flood inundation the tree stumps would have been saturated causing anaerobic conditions and very slow organic decay. In addition, fine helical striae, or checking, can be seen on the tracheid walls, often inclined steeply, throughout the length of the cell (Plate 22, Figure 2). These striae are linked to tracheid wall shrinkage prior to silicification (Jane, 1970).

Variation in the nature of medullary rays between all 32 specimens from the Urawitiki Measures is presented in Table F5, Appendix F. Overall, the number of biseriate medullary rays observed was low, varying from 0 to 7. Medullary ray height varies from 1-17 cells with most generally low, commonly 2-8 cells. The standard deviations of medullary ray height are relatively high (≥2.0 cells) indicating the range of medullary ray heights was also quite high within each specimen.
Remarks:

The distinguishing features of the fossil wood material described above are the numerous and mainly separate, uniseriate bordered pitting on the tracheid radial walls; the small, dentate-margined and variably arranged cross-field pits and the rare biseriate nature of the medullary rays. These specimens differ from *Protocupressinoxylon* sp. A in the mixed nature of the cross-field pitting (despite showing similar dentate margins to the pits), the generally more widely separated tracheid radial wall pitting, the sparse axial parenchyma and lack of tangential pitting. In addition, the rays are rarely biseriate, slightly higher and have a wider height range.

*Mesembrioxylon* sp. described from the Middle Jurassic fossil forest beds at Curio Bay, Southland (Edwards, 1934) is very close in cellular structure to the fossil wood discussed above (Table F2, Appendix F). However, due to poor preservation, Edwards’ (1934) description does not fully indicate the nature of the cross-field pitting, and cannot be described as the same species. Another similar taxon described from the Triassic beds of Kiretehere Beach in North Island, New Zealand, is *Podocarpoxylon paralatifolium* Vozenin-Serra & Grant-Mackie, 1996 (Table F2, Appendix F). *Podocarpoxylon paralatifolium* Vozenin-Serra & Grant-Mackie, 1996 has a similar bordered pitting arrangement, except the pits are mainly contiguous rather than separate. This species also has eye-like or elliptical cross-field pits, rather than mainly circular pits, and has characteristic tapering medullary ray cell end walls which are not observed in the above described Urawitiki Measures material. Only *Protocupressinoxylon vectense* (Barber) Kräusel, 1949 from the Mesozoic of Laurasia has a relatively similar structure (Table F3,
Appendix F). However, *Protocupressinoxylon vectense* (Barber) Kräusel, 1949 has rare biseriate tracheid radial pitting, tangential pitting in the latewood and abundant axial parenchyma which differs from the specimens described above. Therefore, direct comparison of the Kawhia Harbour and Slope Point fossil wood assigned to this morphotype is not possible with any previously described fossil wood taxa from the Mesozoic of Gondwanaland or Laurasia (Tables F2 and F3, Appendix F).

**Known New Zealand Jurassic Occurrence:**

Middle Jurassic: Opapaka Point, Southern Ohanga Bay and Jetty sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis); Slope Point, Southland, Southland Regional Syncline (this thesis).

**FORM GENUS Protopodocarpoxyylon** Eckhold, 1922

*Form genus diagnosis (from Kräusel, 1949):*

Gymnospermous wood with no resin canals. Tracheid bordered pits: round, of mixed type (separate and contiguous), uniseriate; if biseriate, opposite and not hexagonally compressed. Medullary rays uniseriate. Abietinean pitting typically absent. Cross-field pits: commonly 1-2, very large, simple or bordered pits per field. Podocarpoid pitting common in latewood. Axial parenchyma present, sometimes abundant.
Protopodocarpoxylon sp.

Plate 23, Figures 1-4; Plate 24, Figures 1-6.


Histology and Description:
Irregular shaped, in-growth-position (for example, Plate 23, Figure 2) and ex situ silicified specimens, maximum dimension 8 cm (Plate 23, Figure 1). In-growth-position specimens highly carbonaceous with bleached surface, ex situ specimens highly silicified and light brown throughout. Growth rings distinct on transverse and occasionally radial sections in all specimens, but no false or frost rings were observed (Plate 23, Figures 3,4). Each ring has a very narrow LW zone (3-4 cells) and a wide EW zone. There is a gradual EW to LW transition. Ring boundaries are straight or show only minor curvature indicating the in-growth-position samples originated from the outer stump region, and the ex situ samples from the outer trunk. Cellular distortion is common, particularly in the in-growth-position specimens. Rings are composed entirely of tracheid cells. Axial parenchyma was not observed, but this may be a result of poor preservation.
The following cellular description is based on sample VH202 which is the best preserved from those assigned to *Protopodocarpoxylon* sp. (Plate 23, Figure 4; Plate 24, Figures 1-3,5,6). Tracheid cells are arranged in closely packed regular radial files with no intercellular spaces (Plate 24, Figure 1). Undistorted tracheids are mainly quadrangular or rarely circular in cross-section with LW cells becoming tangentially flattened towards the ring boundary. EW cells are radially elongate, especially at the beginning of the growing season. Tracheid length in radial section is indeterminate due to preservation, but they maintain a consistent width. Tracheid end walls taper. Table 4.9 presents the cross-sectional dimensions of the tracheid cells. Cell wall thickness is relatively constant within each cell. The majority of tracheid cells remained resin free prior to silicification.

**Table 4.9** *Protopodocarpoxylon* sp. tracheid overall size, cell wall and cell lumen dimensions (μm).

<table>
<thead>
<tr>
<th></th>
<th><strong>EW</strong></th>
<th><strong>LW</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radial dimension</td>
<td>43.3</td>
<td>13.6</td>
</tr>
<tr>
<td>Average tangential dimension</td>
<td>27.0</td>
<td>23.8</td>
</tr>
<tr>
<td>Radial cell wall thickness (min) mean (max)</td>
<td>(1.7) 3.5 (5.2)</td>
<td>(3.5) 5.5 (8.6)</td>
</tr>
<tr>
<td>Radial cell lumen diameter (min) mean (max)</td>
<td>(29.4) 38.6 (46.6)</td>
<td>(5.2) 8.6 (13.8)</td>
</tr>
<tr>
<td>Average cell wall:lumen ratio</td>
<td>1:11.0</td>
<td>1:1.6</td>
</tr>
</tbody>
</table>

Poor radial preservation exhibited only ghosts of tracheid walls and circular to elliptic bordered pitting (Plate 24, Figures 2-4). The pitting appears uniseriate (mainly contiguous, but also separate; for example, Plate 24, Figures 2,4) with a very rare
biseriate opposite arrangement. An exceptionally preserved, isolated bordered pit shows fine pit detail including raised borders, margo and aperture (Plate 24, Figure 5). No tracheid tangential wall pitting was observed.

Medullary rays are radially extensive (passing through ring boundaries) and are closely, but variably, spaced at an average of 5 tracheid cells apart (Plate 24, Figure 1). Variation in the nature of the medullary rays between specimens is presented in Table F6 (Appendix F). Overall the medullary rays are predominantly uniseriate, with rare partially and centrally biseriate medullary rays (Plate 24, Figure 6). Medullary ray height varies significantly and ranges from 1-53 cells high, with most 3-22 cells. The standard deviations of medullary ray heights are very high, up to 13.7 cells, which indicates a high variance of medullary ray height within each specimen. The medullary ray parenchyma cells appear circular in tangential section, empty of resiniferous contents and of isodiametric proportions within each medullary ray. The uppermost and lowermost medullary ray parenchyma cells are slightly elongate and taper to a point. Average medullary ray cell width = 19.6 μm. The biseriate portions, commonly 3-4 centrally placed cells (rarely more), occur within the longer medullary rays. No cross-field pitting is preserved.

Sample VH205 originated from a large trunk and exhibits an unusual feature in the form of a fossilised bark pocket. Bark pockets result from the death of a region of cambium and the cessation of new wood production in that region. The adjacent cambium still produces new cells which gradually surround the static area and its bark.
Remarks:
The circular, mainly uniseriate (rare biseriate opposite) bordered pitting and predominantly uniseriate medullary rays are features attributed to the *Podocarpoxyylon* Gothan *emend.* Stopes, 1915 form genus. However, the predominantly contiguous arrangement of the bordered pitting suggests a more primitive form assignable to the form genus *Protopodocarpoxyylon* Eckhold, 1922.

The general structure is distinguished from *Protocupressinoxylon* sp. A and *Podocarpoxyylon* sp. A in the mainly contiguous tracheid radial wall pitting, the possibly absent axial parenchyma and the extremely high medullary rays and medullary ray height range. Direct comparison with previously described taxa of similar overall cellular structure from either the Mesozoic of Gondwanaland or Laurasia is difficult due to the incomplete preservation of the samples thin-sectioned. However, *Mesembrioxylon* sp. described from the Cretaceous of Namaqualand, South Africa (Bamford and Corbett, 1994) has similar cellular features (Table F2, Appendix F). It differs from the samples described in having abundant resin filled tracheids and parenchyma, indistinct growth rings and medullary rays up to only 34 cells high.

Known New Zealand Jurassic Occurrence:
Middle Jurassic: Opapaka Point and Jetty sections, Te Maika Peninsula; Totara Peninsula section, Kawhia Regional Syncline (this thesis).
INCERTÆ SEDIS

Gen. indet.

Plate 25, Figures 1-5.


Description and Remarks:

Samples VH134-136, VH181-183, VH191, VH248, VH249 and VH270-275 consist of irregular blocks, of both in situ and ex situ origin, up to a maximum dimension of 11 cm (for example, Plate 25, Figures 1,2). The wood was significantly crushed prior to silicification and is either very coalified or almost completely silicified. Several samples have poorly preserved growth ring boundaries visible to the naked eye, but on stereomicroscopic or thin-section examination these become almost indiscernible with no observable cellular structure.

Sample VH120 was cored from a fossilised trunk fragment within the West Coast section, Te Maika Peninsula, Kawhia Harbour (Figure 2.25(a)). This was the only silicified wood fragment within the lowermost Urawitiki Measures and occurred within
massive sandstone rich in coal streaks. Transverse oriented thin-sections (VH120A and VH120B) show a highly distorted gymnospermous wood structure with distinct ring boundaries along very narrow crushed LW zones. In radial section (VH120C and VH120D), the tracheids appear fragmentary and poorly preserved with degraded cell walls (Plate 25, Figure 3). Tracheid radial pitting and cross-field pitting in fragmentary medullary ray parenchyma cell walls is not preserved. Mainly uniseriate medullary rays up to 21 cells high are seen in the tangential thin-sections (VH120E and VH120F; Plate 25, Figure 4). Resiniferous granules appear to be concentrated within occasional longitudinal cells, perhaps indicating the presence of axial parenchyma. This sample is of gymnospermous-affinity due to the predominance of tracheid cells and occasional axial parenchyma, but it cannot be classified further due to the incomplete preservation of tracheid and medullary ray parenchyma cell wall pitting.

Sample VH250 collected from loose beach debris at the Totara Peninsula section, Kawhia Harbour, exhibits unusual features similar to those found in modern tree burrs (Plate 25, Figure 5). A burr is an irregular wood growth forming from numerous adventitious buds that commonly arise from trunk wounds (Jane, 1970). The adventitious buds do not have a vascular strand which extends to the trunk centre and so form many knots in the wood as the main trunk axis grows and expands in diameter. New branches may grow from shoots that develop from the adventitious buds. The knots are expressed as extremely irregular and contorted wood structure, observed in fossilised form in sample VH250. Several new shoots, from 1-23 mm diameter, can be seen growing out through the burr. Due to the generally contorted wood structure,
cellular details observable on the silicified wood of the new shoots can only indicate a gymnospermous-affinity.

Sample VH251 also collected from loose beach debris at the Totara Peninsula section, Kawhia Harbour, consists of an entirely silicified small stem or branch fragment (originally approximately 18 mm diameter) together with several moulds and casts of indeterminate, small (up to 9 mm valve diameter), ribbed bivalves (Figure 2.224) within a very fine pebble gravel lithology. No cellular details of the silicified wood fragment have been preserved, but it is assumed to be of gymnospermous-affinity due to the fossil flora within neighbouring strata. The bivalve moulds and casts could well have been freshwater molluscs which may have lived in abandoned channel ponds. Unable to cope with the sudden sediment influx the molluscs died in the floods, their valves were transported down river and were then deposited together with other flood debris including broken tree fragments.

Poorly preserved fossil wood of gymnospermous affinity was also collected ex situ from Slope Point, near Curio Bay, Southland. The cellular detail of these samples (VH270-275) was predominantly recrystallised allowing only a broad taxonomic classification.
Summary

The fossil wood collected from both Kāwhia Harbour and Slope Point is preserved by cellular permineralisation in silica. This allows detailed observation of the structure of the original wood cells and the subsequent taxonomic classification of the specimens. Comparisons with extant families of similar wood form suggest that the Tēmaian forests were dominated by gymnosperm trees that were relatives of the present-day Araucariaceae, Cupressaceae and Podocarpaceae. Sedimentological evidence together with the complete silicification of the wood samples suggests a humid environment where silica was easily transported in the groundwater (mobilised from the volcaniclastic component of the river sands) and deposited within cellular walls and interstices with the aid of humic substances in the leaf litter.

Five morphotypes of fossilised wood with gymnospermous structure are identified from the collection using histological characteristics thought to vary insignificantly either within a species, within an individual plant or with changing environmental conditions (see taxonomic list on the following page). Three of the morphotypes (*Araucarioxylon* sp. A, *Protocupressinoxylon* sp. A and *Podocarpoxylon* sp. A) are preserved well enough to exhibit the fine cellular details necessary for the formal description of new species in a future publication. In addition, *Protocupressinoxylon* sp. A and *Protopodocarpoxylon* sp. exhibit the mixed separation of tracheid radial wall bordered pitting characteristic of particularly early forms of Cupressaceae and Podocarpaceae related woods.
Fossil Wood Taxonomic List from the Urawitiki Measures, Kawhia Harbour:

Kingdom PLANTAE
Division TRACHEOPHYTA
Class GYMNOSPERMOPSIDA
Order CONIFERALES
Family Araucariaceae
Araucarioxylon sp.
Family Cupressaceae
Protocupressinoxylon sp. A
Family Podocarpaceae
Podocarpoxyylon sp. A
Protopodocarpoxyylon sp.

Fossil Wood Taxonomic List from undifferentiated Temaikan sediments at Slope Point, Southland:

Kingdom PLANTAE
Division TRACHEOPHYTA
Class GYMNOSPERMOPSIDA
Order CONIFERALES
Family Araucariaceae
Araucarioxylon sp. A
Family Podocarpaceae
Podocarpoxyylon sp. A

Additional fossil wood previously described from the Curio Bay region, Southland (Edwards, 1934; Pole, 1988; Raine and Pole, 1988):

Order CONIFERALES
Family Araucariaceae
Dadoxylon\textsuperscript{1} austral
Order PENTOXYLALES
Pentoxylon sp.

\textsuperscript{1} Synonymous with \textit{Araucarioxylon} (p. 208).
4.24 Fossil Microflora

Introduction

Diverse assemblages of well-preserved terrestrial palynomorphs have been recorded from fine-grained, organic-rich sediments throughout the Urawitiki Measures (Enclosures 1-5) and the Curio Bay section (Figure 2.31). The fossil microflora includes spores, pollen, fungal spores, mycelium remains (fungal hyphae) and fragments of secondary xylem and leaf cuticle. The following analysis provides additional information on the composition of the source vegetation in the Temaikan to complement the fossil macroflora record. Further, comparison of the fossil microflora to the Australian Jurassic palynological zones aids the refinement of the age of the deposits. Methods, taxonomic descriptions, remarks, the occurrence of each taxon recorded within the Murihiku Supergroup and detailed taxonomic lists for both the Urawitiki Measures in Kawhia Harbour and the approximately coeval strata in Curio Bay, Southland, are presented in Appendix G.

Palynological and Natural Composition

Prominent taxa within the Temaikan samples are *Araucariacites* spp. (relative abundance (r.a.) of Kawhia Harbour microflora counted grains = 29.9%; Curio Bay = 35.2%) and *Baculatisporites comaumensis* (Cookson) Potonié, 1956 (Kawhia Harbour = 17.7%; Curio Bay = 35.8%). Other grains occurring in significant proportions in the
fossil microflora of both localities are *Cycadopites follicularis* Wilson & Webster, 1946 (Kawhia Harbour = 7.7%; Curio Bay = 4.6%) and *Alisporites similis* (Balme) Dettmann, 1963 (Kawhia Harbour = 4.4%; Curio Bay = 2.1%). *Alisporites* spp. and *Retitriletes austroclavatidites* (Cookson) Döring, Krutzsch, Mai & Schulz, 1963 are also present in relatively high quantities in the Kawhia Harbour fossil microflora (r.a. of both taxa = 3.3%). Additional significant taxa occurring in the Curio Bay fossil microflora are *Inaperturopollenites turbatus* Balme, 1957 (r.a. = 2.5%) and *Granulatisporites* spp. (r.a. = 2.2%).

Palynomorph morphotypes are compared to the pollen and spores of modern plant groups to estimate the natural affinities and composition of the source vegetation. Difficulties extrapolating information on present-day floras into the geological past have been discussed in Section 4.1. The natural affinities of the palynomorph grains identified in this study are primarily based on interpretations made by Filatoff (1975) on the Australian Jurassic and de Jersey and Raine (1990) on New Zealand Triassic and earliest Jurassic terrestrial palynomorph assemblages. A summary list of the palynomorphs identified from the Kawhia Harbour and Curio Bay study sites can be found below. For detailed systematics and counts refer to Appendix G. The list is arranged using the natural classification scheme of Stewart and Rothwell, 1993.
Microflora taxonomic list from the Urawitiki Measures, Kawhia Harbour, Waikato:

**Kingdom FUNGI**
*Dictyosporites* spp.
*?Didymoporisporonites* spp.
*Exesisporites* sp.
*?Fractisporonites* spp.
‘Halonites’ sp.
*Microsporonites* spp.
*Monoporisporites* spp.
*Polyadosporites* sp.
Reduviaporonites spp.
?Ascomycetes spores
Rust spores
Hyphae fragments

**Division TRACHEOPHYTA**

**Class LYCOPSIDA**

Order ISOETALES
Family PLEUROMEIACEAE
*?Densoisporites* sp.

Order LYCOPODIALES
*Retiritiletes* austroclavatidites
*Retiritiletes* rosewoodensis
*Retiritiletes* seminuris
*Retiritiletes* spp.

Undifferentiated: BRYOPHYTA or LYCOPSIDA
*Foveosporites* moretonensis
*Foveosporites* spp.

**Class FILICOPSIDA**

Order FILICALES
Family DICKINSONIACEAE,
CYATHEACEAE
*Cibotiumspora* jurienensis
*Cyathidites* minor
*Cyathidites* cf. asper
*Cyathidites* spp.

Family GLEICHENIACEAE
*Gleicheniidites* senonicus

Family HYMENOPHYLLACEAE
*Biretisporites* modestus ?
*Biretisporites* cf. potoniaei ?
*Biretisporites* spp. ?

Family MATONIACEAE,
DIPTERIDACEAE,
CHEIROPLEURIACEAE
*Dictophyllidites* mortonii
*Dictophyllidites* cf. crenatus
*Dictophyllidites* spp.

Family OSMUNDACEAE
*Baculatisporites* comaumensis
*Osmundacidites* wellmanii
Continued:

**Undifferentiated FILICOPSIDA**
- Apiculatisporis otapirensis
- Apiculatisporis spp.
- Clavatisporites spp.
- Granulatisporites spp.
- Rugulatisporites spp.
- Verrucosisporites varians

**Undifferentiated: LYCOPSIDA or FILICOPSIDA**
- Anapiculatisporites dawsonensis
- Anapiculatisporites pristidentatus
- Anapiculatisporites spp.
- Neoraistrickia ramosus
- Neoraistrickia suratensis
- Neoraistrickia truncatus
- Neoraistrickia spp.

**Class GYMNOSPERMOPSIDA**

**Order CAYTONIALES**
- Family CAYTONIACEAE
  - Vitreisporites signatus

**Family CORYSTOSPERMACAEAE**
- Alisporites cf. grandis
- Alisporites lowoodensis
- Alisporites similis
- Alisporites spp.
- Indusiisporites cf. parvisaccatus ?

**Order CONIFERALES**
- Family ARAUCARIACEAE
  - Araucaricites australis
  - Araucaricites fissus
  - Araucaricites spp.
  - Callialasporites dampiieri
  - Callialasporites microvelatus

**Family CHEIROLEPIDACEAE**
- Corollina cf. chateaunovi

**Family PODOCARPACEAE**
- Podocarpidites ellipticus
- Podosporites variabilis

**Family TAXODIACEAE**
- Perinopollenites elatoides

**Undifferentiated GYMNOSPERMOPSIDA**
- Cycadopites follicularis
- Cycadopites sp.

Microflora taxonomic list from undifferentiated Temaikan sediments from Curio Bay, Southland:

**Kingdom FUNGI**
- ?Fractisporonites spp.
- Monoporisporites spp.
- Polyporisporites sp.
- Reduviasporonites spp.
- ?Ascomycetes spores
- Rust spores
- Hyphae fragments

**Kingdom PROTISTA**

**Division CHLOROPHYTA**
- Class PRASINOPHYACEAE
- Order PTEROSPERMATALES
- Family TASMANITACEAE
  - Tasmanites sp.

**Kingdom PLANTAE**

**Division BRYOPHYTA**
- Stereisporites antiaquasporites
- Stereisporites spp.

**Division TRACHEOPHYTA**

**Class LYCOPSIDA**
- Sestrosporites sp.
Continued:

Order ISOETALES
Family PLEUROMEIACEAE
  Leptolepidites verrucatus

Order LYCOPODIALES
  Retitriletes australclavatidites
  Retitriletes rosewoodensis
  Retitriletes semimurus

Undifferentiated: BRYOPHYTA or LYCOPSIDA
  Foveosporites moretonensis

Class FILICOPSIDA

Order FILICALES
Family DICKINSONIACEAE,
  CYATHEACEAE
  Cibotiumspora jurienensis
  Cyathidites australis
  Cyathidites minor
  Ischyosporites cf. volkheineri
Family HYMENOPHYLLACEAE
  Biretisporites modestus ?
  Biretisporites cf. potoniaei ?
  Biretisporites spp. ?
Family MATONIACEAE,
  DIPTERIDACEAE,
  CHEIROPLEURIACEAE
  Dictophyllidites mortonii
  Dictophyllidites spp.
Family OSMUNDACEAE
  Baculatisporites comauensis
  Conbaculatisporites sp.
  Osmundacidites wellmanii

Order MARATTIALES
  Marattisporites scabratius

Undifferentiated FILICOPSIDA
  Apiculatisporis spp.
  Granulatisporites spp.

Lophotrilites sp.

Undifferentiated: LYCOPSIDA or FILICOPSIDA
  Anapiculatisporites dawsonensis
  Neoralistrickia truncatus
  Neoralistrickia spp.

Class GYMNOSPERMOPSIDA

Order CAYTONIALES
Family CAYTONIAECE
  Vitreisporites signatus
Family CORYSTOSPERMACEAE
  Alisporites similis

Order CONIFERALES
Family ARAUCARIACEAE
  Araucariacites australis
  Araucariacites fissa
  Araucariacites spp.
  Callialasporites damieri
  Callialasporites microvelatus
  Callialasporites segmentatus
  Inaperturopollenites turbaus?
Family CHEIROLEPIDACEAE
  Corollina cf. chateauonvi
  Corollina simplex
Family PODOCARPACEAE
  Podocarpidites ellipticus
Family TAXODIACEAE
  Perinopollenites elatoides

Undifferentiated
GYMNOSPERMOPSIDA
  Cycadopites follicularis
  Cycadopites sp.
Overall, 84 taxa, including fungi, algae, spores and pollen are recognised, with 38 taxa common to both the Kawhia Harbour and Curio Bay assemblages. Taxa only occurring in the Kawhia Harbour samples totalled 34, while 12 taxa were restricted to the Curio Bay fossil microflora. Table 4.10 presents the differences in abundance of the natural groups within the Kawhia Harbour and Curio Bay assemblages.

Table 4.10  The number of taxa representing each natural taxonomic group that are common to both the Kawhia Harbour (KH) and Curio Bay (CB) fossil microflora assemblages, or that only occur in one.

<table>
<thead>
<tr>
<th>Natural Group</th>
<th>Number of taxa common to both</th>
<th>Number of taxa occurring at KH only</th>
<th>Number of taxa occurring at CB only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bryophyta</td>
<td>2</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Lycopsida</td>
<td>3</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Filicopsida:</td>
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<td>Filicales</td>
<td>9</td>
<td>4</td>
<td>3</td>
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<tr>
<td>Marattiales</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Gymnospermopsida:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caytoniales</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Coniferales</td>
<td>8</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Undifferentiated</td>
<td>6</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

The interpreted natural affinities of the palynomorphs recorded provide evidence for a diverse forest community in the Temaikan terrestrial ecosystem comprising fungi, freshwater algae, bryophytes, lycopsids, ferns and gymnosperms. Table 4.11 presents the total relative abundance of grains from all samples at each locality assigned to natural groups. Both the Kawhia Harbour and Curio Bay assemblages are dominated by grains (and rare tracheid and cuticle fragments) derived from relatives of the Filicales and Gymnospermopsida (particularly the Coniferales). However, there are a significant
number of taxa only found at either locality suggesting differences in the source vegetation composition (Section 4.42).

Table 4.11 Total relative abundance (r.a.) of grains recorded within each natural taxonomic group from both the Kawhia Harbour (KH) and Curio Bay (CB) assemblages.

<table>
<thead>
<tr>
<th>Kingdom</th>
<th>Division</th>
<th>Class</th>
<th>Order</th>
<th>KH r.a. (%)</th>
<th>CB r.a. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fungi</td>
<td></td>
<td></td>
<td></td>
<td>3.52</td>
<td>1.21</td>
</tr>
<tr>
<td>Protista</td>
<td>Chlorophyta</td>
<td>Prasinophyaceae</td>
<td></td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Plantae</td>
<td>Bryophyta</td>
<td>Tracheophyta</td>
<td>Lycopsida</td>
<td>4.39</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Filicopsida</td>
<td>Filicales</td>
<td>5.29</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Marattiales</td>
<td>26.30</td>
<td>40.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gymnospermopsida</td>
<td>Caytoniales</td>
<td>10.35</td>
<td>4.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Coniferales</td>
<td>38.46</td>
<td>40.47</td>
</tr>
</tbody>
</table>

*Palynological Zonation*

The Temaikan fossil microflora assemblages from Kawhia Harbour and Curio Bay contain miospores comparable with those assigned to the Australian *Callialasporites dampieri* Superzone (Helby, et al., 1987). Elements of the microflora from the Urawitiki Measures assemblage suggest similarities with the *Callialasporites turbatus* Oppel-Zone (Helby, et al., 1987). For example, significant proportions of bisaccate pollen and *Araucariacites fissus* Reiser & Williams, 1969, the latter of which is only prominent in the eastern Australia assemblages of Helby, et al., 1987. However, *Corollina torosa* (Reissinger) Balme, 1957 is a prominent component of this zone in Australia and was
not observed at all in the Urawitiki Measures assemblage. The \textit{Callialasporites turbatus} Oppel-Zone is dated as Toarcian to early Bajocian (Helby, et al., 1987).

Significant proportions of \textit{Callialasporites dampieri} (Balme) Sukh Dev, 1961, \textit{Cyathidites} spp. and \textit{Retitriletes} spp. are characteristic of the overlying Middle Bajocian to early or middle Bathonian \textit{Dictyotosporites complex} Oppel-Zone (Filatoff, 1975; modified by Helby, et al. 1987). These palynomorphs also occur prominently in the Urawitiki Measures assemblage (r.a. = 0.47\%, 0.57\% and 5.27\% respectively). Other significant components common to both the Urawitiki Measures and key species of the \textit{Dictyotosporites complex} Oppel-Zone are \textit{Neoraistrickia suratensis} McKellar, 1974 (r.a. = 0.02\%), \textit{Neoraistrickia truncatus} (Cookson) Potonié, 1956 (r.a. = 0.82\%), \textit{Antulsporites varigranulatus} (Levet-Carette) Reiser & Williams, 1969 (r.a. = 0.28\%) and \textit{Rogalskaisporites cicatricosus} (Rogalska) Danzé-Corsin & Laveine, 1963 (r.a. = 0.44\%) (Filatoff, 1975).

The composition of the Urawitiki Measures fossil microfloral assemblage suggests a close comparison to the uppermost \textit{Callialasporites turbatus} Oppel-Zone and the lower part of the \textit{Dictyotosporites complex} Oppel-Zone, implying an early-mid Bajocian age. This interpretation is in agreement with the probable early Bajocian (early-mid Temaikan) age derived from a study of the fossil macrofauna in neighbouring formations (Section 1.32).
The Curio Bay microflora although containing a large proportion of bisaccate pollen, similar to the Kawhia Harbour assemblages and characteristic of the *Callialasporites turbatus* Oppel-Zone (Helby, et al., 1987), does not contain a significant proportion of *Araucariacites fissus* Reiser & Williams, 1969 (r.a. = 0.51%). However, it does contain a significant proportion of *Cyathidites* spp. (r.a. = 1.92%) and *Retitriletes* spp. (r.a. = 1.92%), characteristic of the overlying *Dictyotosporites complex* Oppel-Zone (Helby, et al., 1987). In addition, Filatoff's (1975) original list of key species for the international correlation of this zone includes *Ischyosporites volkheimeri* Filatoff, 1975. The Curio Bay assemblage contains spores that are compared to this species.

The fossil microflora assemblage from Curio Bay could well be part of the *Dictyotosporites complex* Oppel-Zone which is dated as mid Bajocian to early or mid Bathonian. The assemblage could well be derived from close to the base of this zone giving the Curio Bay strata a mid Bajocian (?mid Temaikan) age. Further work is required on the biostratigraphy of both localities and the rest of the New Zealand Jurassic to substantiate these results with range charts.

**Summary**

The terrestrial palynomorph record from the Temaikan sediments at Kawhia Harbour

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1 *Callialasporites* spp. do not show a marked increase in prominence between the Kawhia Harbour and Curio Bay assemblages, as is characteristics of the base of the *Dictyotosporites complex* Oppel-Zone (Helby, et al., 1987).

2 Raine and de Jersey, in progress (pers. commun., 1998).
and Curio Bay consists of fungal, algal and miospore components. It is dominated by grains of Araucariaceae and Osmundaceae affinity and is comparable to Australian palynological zones which suggest an early-mid Bajocian age for the Urawitiki Measures strata and possibly a mid Bajocian age for the undifferentiated sediments exposed at Curio Bay.

4.25 Summary

The Urawitiki Measures at Kawhia Harbour and the strata exposed at Curio Bay both contain a diverse range of fossilised remnants of the New Zealand Temaikan vegetation. Natural affinities have been assigned to most taxa described, except certain palynomorphs with a grain morphology that is known to be produced by more than one group of plants (for example, *Neoraistrickia* spp.). The Cycadales Order is the only natural group present in the fossil macroflora of the Urawitiki Measures (*Taeniopteris daintreei* McCoy, 1874) that is not represented in the fossil microflora at that locality. *Cycadopites* spp. grains could well be the palynomorph representatives of the Cycadales, but their natural affinity cannot be assigned with confidence (Appendix G). The Equisetales and Cycadodeidales represented in the Curio Bay region fossil macroflora are not represented in the fossil microflora of either locality.

The taxonomic lists below summarise the natural plant groups interpreted to have been present within the Kawhia Harbour and Curio Bay region during the Temaikan. The list
includes both fossil macroflora and microflora components identified in this study and additional taxa found only by other authors. For example, the Pentoxylales, an Order of Gymnospermopsida, have been identified as rare components of the fossilised tree stump flora in the Curio Bay fossil forest (Pole, 1988).

Summary list of groups represented in the Urawitiki Measures fossil flora assemblage, Kawhia Harbour:

**Kingdom FUNGI**

**Kingdom PROTISTA**

Division CHLOROPHYTA
Class PRASINOPHYACEAE
Order PTEROSPERMATALES
Family TASMANITACEAE

**Kingdom PLANTAE**

Division BRYOPHYTA
Class ?BRYOPSIDA

Division TRACHEOPHYTA
Class LYCOPSIDA
Order ISOETALES
Family PLEUROMEIACEAE
Order LYCOPODIALES

Class FILICOPSIDA
Order FILICALES
Family DICKINSONIACEAE, CYATHEACEAE
Family GLEICHENIACEAE
Family HYMENOPHYLLACEAE
Family MATONIACEAE, DIPTERIDACEAE, CHEIROPLEURIACEAE
Family OSMUNDACEAE

Class GYMNOSPERMOPSIDA
Order CAYTONIALES
Family CAYTONIACEAE
Family CORYSTOSPERMACEAE
Continued:

Order CONIFERALES
  Family ARAUCARIACEAE
  Family CHEIROLEPIDACEAE
  Family CUPRESSACEAE
  Family PODOCARPACEAE
  Family TAXODIACEAE
Order CYCADALES

Summary list of groups represented in the Curio Bay fossil flora assemblage:

Kingdom FUNGI

Kingdom PROTOISTA
Division CHLOROPHYTA
  Class PRASINOPHYACEAE
  Order PTEROSPERMATALES
  Family TASMANITACEAE

Kingdom PLANTAE
Division BRYOPHYTA
Division TRACHEOPHYTA
  Class LYCOPSIDA
  Order ISOETALES
  Family PLEUROMEIACEAE
  Order LYCOPODIALES
  Class SPHENOPSIDA
  Order EQUISETALES
  Family EQUISETACEAE
  Class FILICOPSIDA
  Order FILICALES
  Family DICKINSONIACEAE, CYATHEACEAE
  Family HYMENOPHYLLACEAE
  Family MATONIACEAE, DIPTERIDACEAE, CHEIROPLEURIACEAE
  Family OSMUNDACEAE
  Order MARATTIALES
  Class GYMNOSPERMOPSIDA
  Order CAYTONIALES
  Family CAYTONIACEAE
  Family CORYSTOSPERMACEAE
Continued:

Order CONIFERALES
  Family ARAUCARIACEAE
  Family CHEIROLEPIDACEAE
  Family PODOCARPACEAE
  Family TAXODIACEAE
Order CYCADALES (Edwards, 1934)
Order CYCADEOIDALES
Order PENTOXYLALES (Pole, 1988)

The fossil plant organs described from Kawhia Harbour and Curio Bay all suggest a Temaikan vegetation dominated by Filicopsida and Gymnospermopsida related plants. The natural taxonomic composition can provide a qualitative estimate of forest structure. For example, the occurrence of fossil wood and fossilised stumps, in growth position, imply trees of Araucariaceae, Cupressaceae and Podocarpaceae affinity, with rare Pentoxylon (Pentoxylales) and Ashicaulis (Filicales) formed an arborescent component to the vegetation community. Further, Caytoniaceae, Corystospermaceae, Cycadeoidales (only observed at Curio Bay), Cheirolepidaceae and Taxodiaceae trees added to the canopy. Fossil macroflora and microflora evidence also implies the presence of smaller\(^1\) gymnosperms (small diameter fossil stumps) with herbaceous ferns, lycopods, horsetails (only observed at Curio Bay) and bryophytes (palynomorphs, fossil leaves and stem fragments) growing on the forest floor. Evidence for the presence of fungi within the ecosystem is also present in the fossil wood and microflora assemblages.

\(^1\) Estimates of plant height are discussed quantitatively in Section 4.44.
Palaeoclimate Implications

The mode of fossil wood preservation (p. 193), in addition to sedimentological (p. 136) and palynological (p. 20) evidence, suggests the climate was humid in the New Zealand region during the Temaikan for at least part of the year and did not undergo extremes of temperatures. Palynological evidence for a mild and wet climate includes the presence of *Stereisporites* spp. and *Gleicheniidites* spp. spores. The occurrence of both taxa imply very wet conditions and high rainfall if we assume the source plants occupied a similar habitat in the Middle Jurassic as they do today (Askin, pers. commun., 1997; p. 20). Moist conditions would also have been essential for the survival of freshwater algae (*Tasmanites* spp.), which may have lived within bar-top pools in the interpreted braided river environment (Figure 2.230). Further, a moist forest floor or damp, decaying wood from the trees would have provided suitable habitats for fungal growth.

The very low content of *Corollina* spp. pollen grains implies low continental temperatures when compared to Vakhrameev’s (1978) findings on Cretaceous palynofloras in southern USSR (Figure 1.25). Only two specimens of *Corollina* cf. *C. chateaunovi* (Reyre) Courtinat & Algouti, 1985 were recorded in the Urawitiki Measures assemblages and three *Corollina* spp. grains from Curio Bay. Therefore, such a minor occurrence of this pollen is not significant enough to compare with Vakhrameev’s (1978) results. In addition, there is evidence from several studies on the ammonite and belemnite fauna of the New Zealand Middle Jurassic that sea temperatures could well have been warm-temperate at this time (for example, Stevens, 1980a, 1985a).
Comparison with other Gondwanaland Jurassic Floras

The Filicopsida and Gymnospermopsida composition of the New Zealand Temaikan flora is comparable to many Jurassic floras described world-wide (Seward, 1931). The occurrence of the fossil macroflora genera *Cladophlebis* (?Osmundaceae), *Elatocladus* (Coniferales) and *Taeniopteris* (Cycadales) is a common feature. Within the Gondwanaland countries, these three genera are known from India (Rao, 1953), Antarctica (Halle, 1913a), Australia (Walkom, 1921a) and elsewhere within the Murihiku Supergroup in New Zealand (Arber, 1917, Raine and Pole, 1988).

The Ginkgoales, a common Jurassic floral element elsewhere, is missing from the New Zealand Temaikan assemblages studied. The absence of Ginkgoales was also noted from the diverse Middle Jurassic or Early Cretaceous Hope Bay flora in Grahamland, Antarctica (Halle, 1913a). The Hope Bay flora contains abundant fern, cycad and conifer related foliage fossils, although of a predominantly different composition to the New Zealand Temaikan assemblage. Absence of Ginkgoales could well have been due to a lack of suitable habitats in these two localities.

The Equisetales and Cycadeoidales, present in the Curio Bay fossil flora do not appear to be part of the Urawitiki Measures flora. However, their absence may be due to physiological factors. For example, the spores of extant *Equisetum* have a relatively low sporopollenin content and so a low preservability. This may have caused non-

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1 Arber (1917) referred to *Cladophlebis australis* Morris, 1845 as “the great weed of Mesozoic times”.
representation of this group in the palynomorph assemblages. Further, the
inconsistencies and rarity of macroflora preservation may simply mean that
representatives of the Equisetales and the Cycadeoidales did exist in the source
vegetation in the Kawhia Harbour region, but were not preserved in the Urawitiki
Measures depositional environment.

4.3 TAPHONOMY

4.3.1 Introduction

Fossil plant-bearing beds are found throughout the Urawitiki Measures at Kawhia
Harbour (Enclosures 1-5) and are grouped into repeatable taphocenoses\(^1\) in the following
section. The mode of incorporation into the sediment (taphonomy) and process of
fossilisation determines how representative each taphocenosis is of a certain area of
source vegetation. Repeated taphocenoses imply that the constituent remains

\(^1\) A repeatable group of dispersed fossil organs occurring within a particular sedimentary facies (after
Krasilov, 1975).
represent plants that originally lived close to one another in a similar habitat. Analysis of successive taphocenoses within the Urawitiki Measures allows a study of composition and habitat changes in the source vegetation through a period of time in the early-mid Temaikan.

### 4.32 Taphocenoses Classification

Fossil plants are found in beds within all of the interpreted sedimentary facies described in Chapter 2 except facies e (sheet flood gravel, upper midfan depositional environment) from the West Coast section, Te Maika Peninsula (Table 2.4). Each taphocenosis identified is described in the following section based on Krasilov’s (1975) classification scheme (terms used are defined below). Enclosure 7 illustrates the distribution of the repeatable taphocenoses throughout the uppermost Urawitiki Measures stratigraphic sections. Sedimentary facies and taphocenoses distribution for the lowermost Urawitiki Measures strata in the West Coast section, Te Maika Peninsula, are presented in Enclosure 1. Detailed sedimentary facies descriptions and fossil plant systematics can be found in Sections 2.2 and 4.2 (plus Appendix G) respectively.

_Taphocenosis Classification Terminology (after Krasilov, 1975)_

**Oligo- / Polyspecific**

Refers to species diversity within the taphocenosis. _Oligo-_ several species are present; _poly-_ many species are present.
**Oligo- / Polydominant**

Refers to the dominant species within the taphocenosis, in terms of numbers. The dominant fossil species do not necessarily correspond to the dominants in the source vegetation. *Oligo-* several species are co-dominant; *poly-* many species are co-dominant.

**Mono- / Oligo- / Polysynusial**

Refers to the number of groups of life forms represented in the taphocenosis (for example, herbaceous plants or arborescent plants, refer to Section 4.43 for a detailed analysis of plant life forms). *Mono-* only one group of life forms is represented; *oligo-* several groups of life forms are represented; *poly-* many groups of life forms are represented.

**Hetero- / Isomeric**

Refers to the size of the fossil plant remains. *Heteromeric* includes remains of all sizes: micro $< 200 \mu m$, meso $200 \mu m - 2 \ mm$, macro $> 2 \ mm$; *isomeric* includes remains in only one size category.

**Euauto- / Hypo- / Allochthonous**

Refers to the distance the fossil plant remains were transported prior to burial. *Euauto-* buried in growth position; *hypoauto-* buried following only insignificant transport; *allo-* buried following significant transport.
Taphocenosis 1

Occurrence:

Siltstone beds within facies a (sheet sand bar, subaqueous fan-delta front) and c (abandoned stream flow channel, lower sub-aerial midfan) (Enclosure 1).

Description:

Fossilised spores and pollen, portions of fossilised tree trunks and branches; dispersed and distributed throughout individual beds; palynomorphs - carbonaceous compressions, aggregate of grains shed from living plants or fungi when entrained, polyspecific, oligodominant, polysynusial; fossilised wood - carbonaceous compressions and silicified, derived from living or dead trees; heteromeric; allochthonous.

Detailed taxonomic composition:

Fossilised wood: Unidentifiable carbonaceous streaks and sample VH120 - silicified, but little detail preserved, so also unidentifiable (Plate 25, Figures 3,4).


Taphocenosis 2

Occurrence:

Matrix-supported conglomerate and sandstone (coarse- to very coarse-grained) beds within facies b (stream flow channel, lower midfan) and d (sheet flood sand, lower-upper midfan) (Enclosure 1).
Description:

Portions of fossilised tree trunks and branches; preserved as carbonaceous compressions; remains dispersed and distributed throughout individual beds; derived from living or dead trees; monosynusial; isomeric; allochthonous.

Detailed taxonomic composition:

Unidentifiable carbonaceous compressions of tree trunk and branch portions.

Taphocenosis 3

Occurrence:

Sandstone (fine- to very coarse-grained) and siltstone beds within facies f (vegetated sub-aerial bar top, sandy braided river) (Enclosures 2-5).

Description:

Fossilised tree and shrub stumps still in growth position with downward radiating roots, portions of tree trunks and branches, tree-fern rhizome fragments, seed cones, individual seeds, leaves, spores and pollen; remains dispersed and distributed throughout individual beds, except fossilised tree stumps which root from the upper bedding surface; preservation - silicified (fossilised wood only), carbonaceous compressions and impressions; heteromeric; taphocenosis could well have resulted from an abrupt burial event, for example, a major flood; fossilised tree/shrub stumps and carbonaceous roots = euautochthonous; leaves, spores and pollen (refer to discussion, Section 4.33) = hypoautochthonous, remainder of taphocenosis = allochthonous; polyspecific; polydominant; polysynusial.
Detailed taxonomic composition:

Fossilised wood: *Protocupressinoxylon* sp. A, *Podocarpoxyylon* sp. A, *Protopodocarpoxyylon* sp., *?Ashicaulis* spp. (71.8% of identifiable in-growth-position tree stump samples are of Cupressaceae affinity)

Fossilised leaf cones and seeds: *Gen. indet.*

Fossilised roots: *?Ashicaulis* spp., *Gen. indet.* (associated with fossil tree stumps still in growth position)


Taphocenosis 4

Occurrence:

Sandstone (medium-grained) and gravel beds within facies g (major sheet flood, sandy braided river) and h (channel fill and migration, sandy braided river) (Enclosures 2-5).

Description:

Fossilised tree and shrub stumps still in growth position with downward radiating roots, portions of fossilised tree trunks and branches, tree-fern rhizome fragments, seed cones; remains dispersed and distributed throughout individual beds, except stumps which root
from the upper surface; preservation - carbonaceous compressions; isomeric; aggregate of organs shed from living plants when entrained; fossilised tree/shrub stumps and carbonaceous roots = euautochthonous, remainder of taphocenosis = allochthonous; oligospecific; oligodominant; oligosynusal.

Detailed taxonomic composition:

Fossilised wood: unidentifiable carbonaceous compressions

Seed cones: Gen. indet.

Roots: ?Ashicaulis spp.

4.33 Taphocenoses Analysis

Urawitiki Measures Taphocenoses 1 and 2

Taphocenoses 1 and 2 only occur in beds of the West Coast section of Te Maika Peninsula which are interpreted as delta-front and midfan depositional environments (Figure 2.217). Both taphocenoses contain allochthonous fossil flora remains derived from the Urawitiki Measures hinterland vegetation that have undergone significant transport and sorting processes, mainly in stream flow but also airborne, prior to deposition. The fossil wood and palynomorph components (xylocenosis and palynocenosis respectively) consist of fossilised plant remains from a mixture of vegetation along the transport paths and represent elements of the original vegetation cover over a wide area.
Krasilov (1975) estimates that allochthonous miospores and large, transportable organs (for example, substantial branches or trunk portions), similar to those that occur within the delta-front and midfan facies, could well have been sourced from an average area of 10 000 km². The allochthonous nature of the West Coast section, Te Maika Peninsula, palynofloras cannot represent the original vegetation from a particular depositional setting, but does represent the dominant taxa. Samples VP946 and VP949 (Taphocenosis 1) were collected from siltstone clasts, which could well have eroded from alluvial sediments upstream of the lower fan-delta and may be representative of a smaller area of hinterland vegetation. However, due to evidence of significant allochthoneity in all the palynomorph samples, the poor fossil wood preservation and no euautochthonous vegetation components, the use of Taphocenoses 1 and 2 for reconstructing the source Urawitiki Measures vegetation is restricted to an estimate of the dominant taxa.

**Urawitiki Measures Taphocenoses 3 and 4**

Taphocenoses 3 and 4 both contain euautochthonous fossil plant components associated with palaeosols (fossilised tree/shrub stumps and carbonaceous roots) implying preservation in growth position. This burial situation suggests only a minimal loss of information, prior to burial, on the woody plant component of the original vegetation community. The mode of preservation in general, suggests that all the stems buried in growth position were preserved (p. 23).
Allochthonous components common to Taphocenoses 3 and 4 include fossilised portions of tree trunks and branches, tree-fern rhizome fragments and seed cones. These dispersed remains could well have been transported to the site of deposition by stream flow and flood waters. The large fossil tree trunk portion (Figure 2.223) may not have travelled far (probably only a few hundred metres) due to its size and the possible entanglement of the root ball with vegetation growing along the river banks, or with other flood debris. However, smaller fossilised trunk or branch portions, tree-fern rhizome fragments and seed cones may have floated for a considerable distance before becoming entrained in sediment. This allochthonous plant debris could well represent elements of the extralocal or regional source vegetation, but much information about composition and structure has been lost during transport.

Taphocenosis 3, in addition to the euautochthonous and allochthonous components already mentioned, contains fossil leaves, individual seeds and palynomorphs, not found in Taphocenosis 4. Individual seeds are considered to be allochthonous, as they could well have floated a considerable distance downstream from the source plant had they fallen in a river channel. Fossil leaves are hypoautochthonous as they probably underwent only minimal aerial transport after falling from the source plant and reaching the entrainment surface. Significant transport of fossil leaves in water is unlikely due to the fragility of the laminae that are commonly preserved intact. Krasilov (1975)
considers the source area of vegetation represented by an autochthonous\textsuperscript{1} sample of leaves is approximately 700 m\textsuperscript{2}.

The size of the source area for fossil miospore assemblages is considered to be at least of regional extent with the locally sourced grains indistinguishable from those carried into the area by air currents above the canopy. However, the majority of the miospores entrained in the depositional settings of the uppermost Urawitiki Measures, Kawhia Harbour and Curio Bay are considered to have accumulated relatively local to their source plants. Local deposition could well have resulted from the presence of sizeable trees on the braidplain (known from the in-growth-position fossilised tree stumps) which would have caused physical barriers to airborne spore and pollen grains produced from plants either within or below the canopy. From studies on surface samples from extant forest floors, it has been estimated that horizontal transport between tree trunks prevails. Further, that the bulk of the pollen comes from a radius of a few hundred metres away (Tauber, 1967a), or much less, possibly equivalent to the height of the trees (Andersen, 1967). Further, there is a high abundance of sculptured trilete spores (for example, \textit{Baculatisporites comaumensis} (Cookson) Potonié, 1956) within the assemblages, which are not well-adapted to airborne transport.

The regional component of the palynomorph assemblages, although indistinguishable from the locally sourced grains, could well be minimal in the forest settings of Kawhia.

\textsuperscript{1} In the context of local vegetation reconstruction, \textit{euautochthonous} and \textit{hypoautochthonous} fossil plant organs are both considered \textit{autochthonous}. 
Harbour and Curio Bay in the Temaikan. The grains borne by wind over the canopy would only reach the forest floor (the entrainment surface) in small amounts, mainly in raindrops. Studies on extant plants show that at least 95% of pollen falls out of the air, even in an unforested area, well within 1 km of the producing plant (Traverse, 1988). Therefore, the regional component of the fossil microflora assemblages in the uppermost Urawitiki Measures and Curio Bay sediments is interpreted to be minimal and the palynocenoses are considered autochthonous vegetation remains. Krasilov (1975) considers the area of vegetation cover represented by an autochthonous miospore sample is 30 000 m² and, in general, such a sample contains representative grains from all the main tree species in the source area.

Taphocenosis 4 represents water-sorted plant debris that has either fallen into the river channels during normal flow or has been detached from plants during a flood event. Therefore, the fossilised material represents only a selection of organs from a few plants in the source vegetation and includes only those that are robust enough to survive possibly very fast flowing currents. The euautochthonous fossilised tree stumps in this taphocenosis root from the upper bedding surface and suggest recolonisation of the new flood sediment surface or channel fill following flood water drainage. Therefore, only the in-growth-position fossilised tree stumps from this taphocenosis are representative of the source vegetation.
4.34 Summary

The loss of information, mainly during transport and prior to burial, renders the allochthonous component of the taphocenoses unrepresentative of the source vegetation. However, the autochthonous components of the fossil macroflora imply the successive regeneration of forests composed dominantly of ferns and gymnosperms. The low fossil macrofloral diversity (Sections 4.22 and 4.23) is contrary to the high diversity represented in the fossil microflora of both localities (Section 4.24) despite the wider source area of the latter. The loss of information about the source vegetation can be substantial between burial and collection even in autochthonous remains, so the palynomorph assemblages are considered to be the most representative of the composition of the original vegetation in both the Kawhia Harbour and Curio Bay regions during the Temaikan.

The use of palynomorph taxa abundance from grain counts is affected by many factors. For example, the local pollen production (some taxa may be over-represented), what is preserved (grains with thin exines or a low sporopollenin content may be under- or non-represented) and what pollen is transported in from outside the local area. The distortion of information about the original vegetation from palynomorphs can also occur due to unknown physiological factors including miospore productivity and flowering frequency of the source plant. Further the sedimentary environment influences the content of the assemblage, for example, a relatively acid, reducing, anaerobic and static sediment surface is required for adequate miospore entrainment and preservation. Multivariate
statistics and equations used in Quaternary and Holocene pollen analyses to correct for pollen productivity and background influences provide an estimate of the proportions of individual taxa within the source vegetation. These methods cannot be applied as far back as the Mesozoic (refer to the discussion in Krasilov, 1975). Therefore, only a non-quantitative interpretation of the taxonomic composition of the source Temaikan vegetation is possible from the fossil microflora.

4.4 PALAEOGEOBOTANY

4.41 Introduction

Palaeogeobotany involves the reconstruction of plants within a fossil ecosystem. The taxonomic composition of the Temaikan vegetation has already been reconstructed from a systematic study (Section 4.2) of the fossil plants from the New Zealand study sites. In addition, a taphonomic analysis on the exposed and collected Urawitiki Measures fossil flora has shown the in-growth-position fossil stumps, leaves and especially the palynomorphs to be highly representative of the original vegetation. However, a knowledge of community associations and life form structure is necessary to complete the vegetation cover reconstruction at these localities.
The following section investigates taxonomic groupings within the vegetation communities at both sites and their stratigraphic and lateral distribution throughout the fossil forest generations. Further, an investigation of plant life forms from studies of the fossil plant remains and work by previous authors provides an estimate of the vertical structure of the vegetation. The fossilised tree stumps preserved in growth position provide evidence of the spatial distribution of trees within the fossil forests. This latter information is useful from a palaeoecological aspect for the interpretation of growth ring sequences from fossil wood (Chapter 5). A pictorial model of the local community succession is then reconstructed to summarise the information interpreted on the form, structure and succession of the source vegetation in relation to the abiotic environment.

4.42 Plant Association

Plant associations are groups of plants that consistently grow together within a specific environment, or adaptive zone; for example, bogs or river valleys. Plant associations can be recognised by the successive transition of taxa in autochthonous palynocenoses. Stratigraphically successive and laterally distributed palynocenoses from the Ohanga Bay sections, Te Maika Peninsula and from Totara Peninsula are investigated in the following section to determine plant associations through time and also their lateral distribution in the Kawhia Harbour region. The Curio Bay palynocenoses are also compared to those at Kawhia Harbour to investigate whether their respective compositions imply a common source vegetation. Plant associations are then related to
the host sedimentary facies for an interpretation of the vegetation setting within the abiotic environment.

The method for assessing whether stratigraphically and laterally successive autochthonous palynocenoses belong to the same plant association involves an analysis of taxonomic similarity. This is achieved by comparing the actual with the theoretical number of common taxa in two successive or laterally related palynocenoses. Preston's (1948) formula is employed to calculate the theoretically expected number of common species from two taphocenoses that are assumed to be from the same association:

\[
N_{a+b}^{1/z} = N_a^{1/z} + N_b^{1/z}
\]

where \( N_a \) and \( N_b \) are the numbers of taxa in two samples taken from the same association, \( z \) is a constant that with a logarithmically normal distribution is equal to 0.27, \( N_{a+b} \) is the expected total number of taxa. The sum of \( N_a \) and \( N_b \) minus \( N_{a+b} \) then provides the theoretically expected number of common taxa. If this final figure compares well to the actual number of common taxa between \( N_a \) and \( N_b \), then it is likely that the two samples represent parts of the vegetation from the same association.

Stratigraphically successive palynocenoses from the Ohanga Bay sections on Te Maika Peninsula, Kawhia Harbour (Figure 4.41, Enclosures 3 and 4) have been analysed using Preston's (1948) formula. The similarity between the actual and the theoretically
Figure 4.41 Detailed graphic log of the Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour, to show the exact stratigraphic locations of the terrestrial palynomorph samples. For further sedimentological and palaeobotanical information on this stratigraphic section, refer to Enclosure 3.
expected number of common taxa (not including fungal or algal spores) is very close in all the calculations (Table 4.12). Further, palynocenoses at similar stratigraphic levels in the Ohanga Bay sections, Te Maika Peninsula and the Totara Peninsula section indicate approximately equal results. The close similarity between the actual and expected numbers of common taxa implies that the autochthonous Urawitiki Measures palynocenoses are all derived from the same original plant association.

A comparison between the allochthonous palynocenoses of the West Coast section and autochthonous palynocenoses from the uppermost Urawitiki Measures also indicates that the miospores were derived from the same original plant association. The assemblage is more diverse in the allochthonous samples (Appendix G) which reflects the much larger source area.

The Urawitiki Measures plant association includes fossils representing all the taxonomic groups summarised in Section 4.25 from both the macroflora and microflora fossil record. This plant association covered an area at least 4 km in width (the geographical distance along strike from the Opapaka Point section, Te Maika Peninsula to the Totara Peninsula section\(^1\)). The palynocenoses are all part of Taphocenosis 3 which occurs within the facies representing a vegetated sub-aerial bar top in a sandy braided river. It is logical that only one plant association in this specific habitat is represented in the fossil microflora. Therefore, the sandy braidplain extending at least between Te Maika

---
\(^1\) Comparison between the Opapaka Point, Ohanga Bay and Totara autochthonous palynocenoses suggests the Opapaka Point section miospores were also derived from the same plant association as the Ohanga Bay, Te Maika Peninsula and Totara Peninsula sections.
and Totara Peninsulas during the early-mid Temaikan was vegetated with a single plant association.

Table 4.12  Actual and theoretically expected numbers of common taxa between stratigraphically and laterally distributed autochthonous palynocenoses in the Ohanga Bay sections, Te Maika Peninsula and the Totara Peninsula section, Kawhia Harbour. Samples listed in stratigraphic order. Refer to Enclosures 3 and 4 for exact stratigraphic location of samples and to Appendix G for detailed taxonomic lists.

<table>
<thead>
<tr>
<th>Palynocenoses compared (sample numbers)</th>
<th>Total number of taxa</th>
<th>Actual number of common taxa</th>
<th>Theoretically expected number of common taxa</th>
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</thead>
<tbody>
<tr>
<td>Northern Ohanga Bay, Te Maika Peninsula (stratigraphically successive)</td>
<td>VP963 24</td>
<td>13</td>
<td>15</td>
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<td></td>
<td>VP962 17</td>
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<td>VP962 17</td>
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<td>VP960 34</td>
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<td>VP960 35</td>
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<td>VP959 37</td>
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<td></td>
<td>VP958 36</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Southern Ohanga Bay, Te Maika Peninsula (stratigraphically successive)</td>
<td>VP956 13</td>
<td>11</td>
<td>12</td>
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<tr>
<td></td>
<td>VP955 27</td>
<td>8</td>
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<td>VP954 9</td>
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<td></td>
<td>VP953 37</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Northern (VP963) and Southern (VP956) Ohanga Bay sections, Te Maika Peninsula; Totara Peninsula (VP964) section (similar stratigraphic level; laterally distributed)</td>
<td>VP964 25</td>
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<td>VP956 13</td>
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<td>VP963 24</td>
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A similar investigation of the palynomorph assemblages from Curio Bay reveals a different plant association than that at Kawhia Harbour. Preston's (1948) formula indicates significant differences between the actual and expected numbers of common taxa, despite the high numbers of common taxa between the two localities (Table 4.13). A comparison between samples collected from Curio Bay yields assemblages interpreted to be from one plant association (samples VP966 and VP967) and also one sample that could well have been derived from a second association (sample VP969). However, only a small number of samples was able to be collected from this locality due to the short stratigraphic section and only three from five samples yielded a high enough diversity for analysis\(^1\). Therefore, only broad interpretations about source plant associations can be made from the Curio Bay material.

It is expected that the palynocenoses from Kawhia Harbour and Curio Bay are from different plant associations due to their slight difference in age (Section 1.32) and their different palaeogeographical locations, despite their similar depositional environments. The relatively high number of common taxa between the Kawhia Harbour and Curio Bay assemblages implies the vegetation cover over the New Zealand region evolved slowly during the early-mid Temaikan.

\(^1\) Sample VP965 yielded only 4 taxa and sample VP968 only 5 taxa (Appendix G).
Table 4.13  Actual and theoretically expected numbers of common taxa between stratigraphically successive autochthonous palynocenoses at Curio Bay, Southland and a comparison with samples of similar diversity from the Ohanga Bay sections, Kawhia Harbour. Samples from Curio Bay listed in stratigraphic order. Refer to Figures 2.31, 4.41 and Enclosure 4 for exact stratigraphic location of all samples, and to Appendix G for detailed taxonomic lists.

<table>
<thead>
<tr>
<th>Palynocenoses compared (sample numbers)</th>
<th>Total number of taxa</th>
<th>Actual number of common taxa</th>
<th>Theoretically expected number of common taxa</th>
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<tr>
<td>Curio Bay (stratigraphically successive)</td>
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<td>VP966</td>
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<td>Comparison with Kawhia Harbour palynocenoses:</td>
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<td>VP961</td>
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<td>VP966</td>
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4.43  Plant Life Forms

The restoration of life forms (approximate size, shape and characteristics of the original plant) is essential for vegetation reconstruction. Life forms can be restored by finding fossil plant organs in a common taphocenosis either in organic connection or separated, but with structural similarities, for example, epidermal features. Non-representation of
particular organs in the fossil record is often accounted for with estimates based on morphological, palaeogeographic and taphonomic data (Krasilov, 1975). Restorations also commonly involve comparison with the life forms of extant relatives allowing for a sufficiently complete reconstruction.

The majority of species are characterised by a single life form, but several life forms may be identified within a genus or family (Meyen, 1987), necessitating the study of many specimens. However, the incompleteness of the fossil record generally only allows the classification of life forms to be broad and the original plants are referred to as being a *tree*, *shrub* or *grass (herb)* and having an *arborescent*, *shrubby* or *herbaceous* habit. These terms indicate a notion of the size of the aerial part of the plant, for example, a stem > 8 cm in diameter is referred to as a *tree* (p. 24).

The Temaikan fossil macroflora specimens from Kawhia Harbour and the Curio Bay region are of low overall diversity. Commonly only one organ occurs in each taphocenosis, for example, no stem or roots assignable to the plant bearing *Cladophlebis* cf. *australis* Morris, 1845 fronds were identified in Urawitiki Measures taphocenoses. Therefore, this study uses life form reconstructions from previous fossil flora studies and habits based on the extant relatives of the fossil remains. The following section describes and illustrates the life forms interpreted for the Temaikan Kawhia Harbour and Curio Bay region plants.
The Fungi and Prasinophyaceae algae are represented only by spores in the palynocenoses which provide no direct evidence for their original life forms. The occurrence of these organisms in the fossil forest ecosystems is important, but a pictorial reconstruction is not necessary due to their minor proportion within the overall vegetation (Appendix G).

The Bryophyta are represented in the fossil macrofloral record of the Urawitiki Measures and the fossil microflora of both Kawhia Harbour and Curio Bay. The fossil macroflora specimen (sample VH167) suggests an herbaceous habit with small stems (at least 9 mm high) similar to extant bryophytes (Plate 1, Figure 1). Further, *Stereisporites* spp. spores from both localities are comparable in morphology to the spores of extant *Sphagnum* mosses suggesting a similar life form (Figure 4.42; Askin, pers. commun., 1997).

The Lycopsida are represented in both the fossil microflora and macroflora assemblages. The palynomorph record includes grains comparable to relatives of both the Isoetales and the Lycopodiales. Members of the Lycopsida (particularly the Lepidodendrales) had an arborescent habit in the Palaeozoic, for example, *Lepidodendron* of the Upper Carboniferous swamps of Europe and North America, Stewart and Rothwell, 1993. However, herbaceous evolutionary lines grew in parallel and the Lycopodiales and Isoetales are thought to have been relatively small, herbaceous plants in the Mesozoic (Seward, 1931, Meyen, 1987). The fossil macroflora example of a small stem from
Figure 4.42  The life form of extant *Sphagnum* moss - Bryophyta. Scale not provided with original figure. From Stewart and Rothwell, 1993.

Slope Point, Southland is consistent with this interpretation (Figure 4.21(a). The life form of the Lycopodiales is depicted by that of the extant *Lycopodium annotinum* and that of the Isoetales by the reconstruction of the Triassic *Pleuromeia sternbergi* (Figure 4.43). The sole extant genus of the Isoetales, *Isoetes*, lives in marshy or aquatic habitats in areas with generally cool climates (Stewart and Rothwell, 1993).
Figure 4.43  Life forms of the Lycopsida. Scale not provided with original figure. From Stewart and Rothwell, 1993.

a) Extant *Lycopodium annotinum* - Lycopodiales.

b) Triassic *Pleuromeia sternbergi* - Isoetales affinity.

The sole representative of the Sphenopsida Class, *Equisetites hollowayi* Edwards, 1934, observed as stem fragments from the Curio Bay strata can be compared to the form of extant *Equisetum* (Figure 4.44). Most reconstructions from fossil remains are from the Palaeozoic and considered too primitive for an adequate Middle Jurassic reconstruction.
The Filicopsida are predominantly represented by both macroflora and microflora fossils of Filicales affinity from the Temaikan of Kawhia Harbour and Curio Bay. The fossil macroflora contains frond fragments of Osmundaceae affinity with bipinnate sterile fronds (*Cladophlebis* spp., Plates 1,3-5). Rhizome fragments of *Ashicaulis gibbiana* (Kidston & Gwynne-Vaughan) Tidwell, 1994 and *Ashicaulis* sp. suggest that the original plants could well have been arborescent (Plate 2; Figures 1,2; Plate 5, Figures 3,4).
No fertile fern fronds were found in the fossil macroflora from either Kawhia Harbour or Curio Bay, but spores considered to be related to the Osmundaceae (*Baculatisporites comaumensis* (Cookson) Potonié, 1956) are abundant in the fossil microfloral assemblages from both localities (Appendix G). A complete frond of *Cladophlebis hochstetteri* (Unger) has been reconstructed from fossil remains within the Upper Jurassic Huriwai Group flora at Port Waikato (~75 km north of Kawhia Harbour) (Figure 4.45(a); Broekhuizen, 1984). The gross morphology of the reconstructed frond suggests a similarity to that of the *Cladophlebis*-type fronds from the Temaikan of Kawhia Harbour and Curio Bay.

Spores that may be related to either Dickinsoniaceae or Cyatheaceae are found in the palynocenoses from both localities (*Cibotiumspora jurienensis* (Balme) Filatoff, 1975, *Cyathidites* spp. and *Ischyosporites* cf. *volkheimeri* Filatoff, 1975), suggesting the presence of further ferns with an arborescent habit in the Temaikan vegetation (Stewart and Rothwell, 1993). Ferns with a non-arborescent or herbaceous habit, represented in the palynocenoses, include relatives of the Gleicheniaceae (*Gleicheniidites senonicus* Ross, 1949), Hymenophyllaceae (*Biretispores* spp.) and Matoniaceae/Dipteridaceae/Cheiropleuriaceae (*Dictyophyllidites* spp.) families. Extant Gleicheniaceae are characterised by dichotomous fronds (Figure 4.45(b); Stewart and Rothwell, 1993) and tend to live in clearings or on the edges of forests together with the Matoniaceae/Dipteridaceae/Cheiropleuriaceae-related ferns (Krasilov, 1975). The Matoniaceae/Dipteridaceae are characterised by fronds which radiate from the tip of the petiole, for example, the Upper Triassic *Phlebopteris smithii* (Figure 4.45(c)). Extant
members of the Cheiropleuriaceae have bat-wing like fronds, for example, *Cheiropleuria biscuspis* (Figure 4.45(d)). The Hymenophyllaceae are not firmly identified in the fossil record, but modern relatives, known as *filmy ferns* are characterised by their thin, often translucent, fronds. They commonly grow in mats on trunks and rocks in damp areas.

Marattiales ferns are represented by the alete spore *Marattisporites scabratous* Couper, 1958 in the Curio Bay palynoceneses. Leaves of extant Marattiales ferns are usually large, up to 4 m long and pinnately compound (Stewart and Rothwell, 1993). Compression-impression fossils of Marattiales foliage in Mesozoic sediments are identical to modern genera, so the habit of *Angiopteris evecta* (Figure 4.46), a plant ~2 m high, is considered a reasonable estimate of the Temaikan life form of these ferns.

Plant remains related to the Gymnospermopsida in the fossil macroflora of the Kawhia Harbour and Curio Bay Temaikan sediments are of Coniferales, Cycadales and Cycadeoidales affinity. Fossilised wood, including tree stumps, from both localities are identified as having Araucariaceae, Cupressaceae and Podocarpaceae affinity. Pollen grains which could well be related to the Araucariaceae and Podocarpaceae are also found in the palynoceneses (for example, *Araucariacites australis* Cookson ex Couper, 1953 and *Podocarpidites ellipticus* (Cookson) Couper, 1953). Extant Cupressaceae (for example, the New Zealand *Libocedrus* genus) and Podocarpaceae (for example, the New Zealand *Podocarpus* or *Dacrydium* genera) are generally relatively tall trees, with the latter rarely adopting a shrubby habit. The extant Araucariaceae (for example, the New
Zealand *Agathis*) are characterised by trees with helically arranged leaves and whorled main branches.

**Figure 4.45**  Life form reconstruction of Filicales-related ferns. Scale not provided with original reconstructions (b)-(d).


The Cycadales, although not formally represented in the microflora, are present in the fossil macroflora as leaf remains (*Taeniopteris daintreei* McCoy, 1874). An Upper Triassic cycad bearing leaves of the *Taeniopteris* type has been reconstructed by Florin (1933) (Figure 4.47(a)). The tree has a leafy crown surrounding the trunk apex which has a cluster of spirally arranged megasporophylls (*Palaeocycas*) at its centre. The imaginary trunk of the reconstructed tree, named *Bjuvia simplex*, is unbranched in the illustration.

The Cycadeoidales are represented in the fossil macroflora of the Curio Bay assemblage by *Ptilophyllum acutifolium* Morris, 1840 leaves. Of the two families of the Cycadeoidales, Williamsoniaceae is the older with fossil representatives occurring in Upper Triassic and Jurassic strata\(^1\) (Stewart and Rothwell, 1993). *Williamsonia*

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\(^1\) The Cycadeoidaceae first appear in the Late Jurassic (Stewart and Rothwell, 1993).
*sewardiana* (Figure 4.47(b)) with a slender, branched stem is considered a reasonable reconstruction of the life form of the Temaikan Cycadeoidales.

Gymnospermopsida families only represented by pollen grains in the fossil microflora include members of the Caytoniales (Caytoniaceae and Corystospermaceae) and the Coniferales (Cheirolepidiaceae, Taxodiaceae). The Caytoniaceae family includes plants
with palmate, compound leaves of the *Sagenopteris* type (Figure 4.47(c)), but no formal reconstruction of the whole plant has been attempted. Similarly the Corystospermaceae have not been formally reconstructed, but are associated with *Dicroidium* foliage (planate, bipinnate fronds), for example, *Dicroidium lancifolia* from the Jurassic of South Africa (Figure 4.47(d); Thomas, 1933). Stems (for example, *Rhexoxylon*¹), although not recognised in the Temaikan horizons, have been found up to 25 cm diameter in the Triassic of South Africa (Meyen, 1987), implying an arborescent habit for the Corystospermaceae. Cartoons of the Caytoniales trees are used in the vegetation palaeoprofile (Section 4.45).

The Cheirolepidaceae (Coniferales), rarely represented in the Temaikan palynocenoses from Kawhia Harbour and Curio Bay (*Corollina* cf. *chateaunovi* (Reyre) Courtinat & Algouti, 1985 and *Corollina simplex* (Danzé-Corsin & Laveine) Reiser & Williams, 1969), have been reconstructed in full by Francis (1983) from dispersed organs in the Jurassic Purbeck Formation of Southern England (Figure 4.48(a)). A full reconstruction of a Jurassic member of the Taxodiaceae family has not been attempted. However, Harris (1979) noted the similarity of *Elatides* fossils in the Yorkshire fossil flora (abundant from the Middle Jurassic to the Lower Cretaceous) to extant *Cunninghamia*, a member of the Taxodiaceae family. Despite the lack of *Elatides* in the New Zealand Temaikan fossil macroflora, the palynomorph record implies that Taxodiaceae trees did exist in this region at the time and could well have attained a similar life form to their

¹ *Rhexoxylon* is considered to be of Corystospermaceae affinity by Meyen (1987), but the vascular morphology of *Rhexoxylon piatnitzkyi* closely resembles the structure of the Pentoxylales (Archangelsky and Brett, 1961).
Northern Hemisphere relatives. A cartoon life form based on extant Taxodiaceae trees is used in the vegetation palaeoprofile (Section 4.45). For the purposes of this study, both the Cheirolepidaceae and Taxodiaceae tree reconstructions are considered valid general forms to represent these families.

An additional member of the Curio Bay flora not observed in this study, but found by Pole (1988) is *Pentoxylon* sp.; a Gymnospermopsida and representative of the Pentoxylales Order. Sahni (1948) reconstructed a *Pentoxylon* plant from portions of permineralised stem from the Lower and Middle Jurassic in India. This *Pentoxylon sahnii* (Figure 4.48(b)) is considered a reasonable estimation of the life form of the Curio Bay material described by Pole (1988).

![Figure 4.48](image-url)  
**Figure 4.48** Life form reconstruction of Gymnospermopsida plants.  
a) Jurassic *Protocupressinoxylon purbeckense* - Cheirolepideaeae, Coniferales affinity. Scale bar = 3 m. After Francis, 1983.  
b) Lower and Middle Jurassic *Pentoxylon sahnii* - Pentoxylales. Scale not available. From Stewart and Rothwell, 1993.
The form of the fossil stumps and roots preserved in growth position at Kawhia Harbour provide additional information about the environmental setting of the early-mid Temaikan forest. For example, symmetrical stump circumferences and a lack of reaction wood in fossil wood samples, indicate a relatively level topography over the braidplain at this locality. Further, the hypothesis of forest horizon preservation (Figure 2.231) suggests the majority of trees died due to slow-draining flood waters. Therefore, either the trees did not live long enough during a prolonged flood to develop stump bulges at their submerged bases, did not have this adaptive ability, or simply died due to intolerance to waterlogging. A similar situation is envisaged for the Curio Bay fossil forest although stump asymmetry at this location has been caused by burial deformation.

4.44 Forest Structure

Reconstruction of the vertical structure of the Kawhia Harbour and Curio Bay fossil forests is possible using the diameters of the in-growth-position fossil tree stumps to estimate tree height. Preservation in growth position also allows forest density to be estimated from the spacing of the fossil stumps over the fossil forest floor, taking into consideration the physiological and taphonomic factors discussed in Section 1.2.

Kawhia Harbour Fossil Forests Vertical and Lateral Structure

Throughout the five stratigraphic sections in the uppermost strata of the Urawitiki Measures (Enclosures 2-5), 236 individual fossil stumps were recognised, all preserved
in growth position. The majority of the fossil stumps were tree-sized ($\geq 0.08$ m diameter), but 11 shrub-sized stems ($< 0.08$ m diameter) and one close group of tree-fern stumps were also recognised (Tables H1-H5, Appendix H). The majority of the fossil stumps are exposed in stratigraphically successive horizons on the shore platform. The lateral distribution of mapped fossil stumps, within the prominent exposed horizons are presented in Enclosures 8-10.

The diameter of all the fossilised tree stumps observed at Kawhia Harbour was measured at the trunk base (where possible) above the stump root flare. Bark and possibly phloem could well have rotted away prior to fossilisation. Pole (1999) estimates that, increasing the measured diameter by 20% would be a closer estimate of the stem's actual diameter in life. Further, the measured diameter does not take into account compression of the wood on burial, or the fossilisation process itself which may have altered the cell sizes. However, due to the predominantly circular fossil trunk cross-sections and the variability and uncertainty of such corrections, the diameter as measured is considered a reasonable estimate of the original size in this study.

Mosbrugger, et al. (1994) estimate tree height for a Miocene fossil forest in Germany using an equation which determines one-fourth of the critical buckling length in a column of a specific radius. Pole (1999) considers this equation provides an underestimate of tree height due to the derivation of the original equation from champion trees in the United States which could well have deviated substantially from their basic architectural model (McMahon and Kronauer, 1976). In addition, extant tree height is
affected by taxonomic composition and forest situation. For example, competition for light may cause one tree to grow very tall in relation to its crown or stem diameter in order to take advantage of a narrow gap in the canopy.

The original Mosbrugger, et al. (1994) tree height equation is considered the most appropriate for the Temaikan trees due to the magnitude of net wood productivity estimates for the Kawhia Harbour fossil trees discussed in Section 5.6. If the Mosbrugger, et al. (1994) tree height estimates doubled, as Pole (1999) suggests, the net wood productivity estimates would be greater than the maximum possible within the interpreted palaeoenvironment and light regime at ~75° South. Further, a stem of diameter 0.08 m, at the forestry-defined shrub/tree boundary, produces a height estimate of 4.47 m with the original Mosbrugger, et al.’s (1994) equation. Pole’s (1999) amended version of the equation doubles the height estimate to 8.94 m, which is very tall for a shrub! Therefore, the original version of Mosbrugger, et al.’s (1994) tree height versus trunk diameter relationship is used in this study. The equation reads:

\[ L = 0.32(E/w)^{1/3}r^{2/3} \]

where \( L \) is the tree height estimation (metres), \( E \) is Young’s modulus, \( w \) is the specific weight and \( r \) is the trunk radius (metres). Young’s modulus and the specific weight are unknown for fossil trees and are highly species dependent. However, Mosbrugger, et al. (1994) argue that the ratio \( E/w \) is relatively constant and they use \( E/w = 1.7 \times 10^6 \) m in their study of Miocene trees in Germany, which corresponds to a typical extant conifer
value. Tree height estimates, using the above equation, for both the Kawhia Harbour and Curio Bay fossil forests, are presented in Appendix H.

The minimum fossil tree stump diameter is 0.08 m within the Kawhia Harbour fossil forest horizons; which is the shrub/tree boundary. The maximum fossil tree stump diameter is 1.10 m (equivalent to a tree 25.6 m high) implying the original plant was an old, well-established tree. The wide distribution of fossil tree stump diameters between these limits (Tables H1-H5, Appendix H) suggests that the forest was actively regenerating with young plants growing up from the forest floor to replace larger, older trees. Figure 4.49 illustrates the frequency of fossil stump diameters throughout the Urawitiki Measures. The mean fossil stump diameter is 0.3 m, although the fossil stumps from the Totara Peninsula section are slightly smaller with an average stump diameter of 0.23 m.

![Diagram](image)

**Figure 4.49** A graph to indicate fossilised stump diameter frequency (including measurable shrub-sized stumps) within the Urawitiki Measures fossil forest horizons at Kawhia Harbour.
Estimates of tree height when reconstructing vertical forest structure are only relevant within individual fossil stump horizons, as each represents contemporaneous tree growth. Each horizon exposed represents only a random section through a fossil forest floor. However, in horizons traceable laterally over some distance, containing a large number of fossil tree stumps, a reasonable estimate can still be made of the forest structure at the time of growth. For example, horizons SOA3 (Southern Ohanga Bay section, Te Maika Peninsula) and TA (Totara Peninsula section) contain many fossil tree stumps (15 and 21 respectively; Tables H3 and H5, Appendix H). The tree height estimates suggest a multi-layered vertical structure to the Urawitiki Measures forest (Figure 4.410). The majority of the trees are estimated as being between 5 and 10 m high, which suggests a foliage canopy at this level. Rare, scattered trees extend above this level at varying heights and could well have partially shaded the understorey. There is no indication that a particular taxon dominated either the canopy or the emergent trees. It is also evident from Figure 4.410 that the trees at Totara Peninsula did not reach the heights of the Te Maika Peninsula trees.

By restricting the estimate of plant height to tree-sized stems, the undergrowth and herbaceous plants are not represented in the transects (Figure 4.410). However, 11 remains of in-growth-position fossil shrub-sized stems and a single close group of fossil tree-fern stumps were also observed. The sparse occurrence of shrub-sized fossilised stems implies that the undergrowth could well have been restricted, perhaps due to
Figure 4.410 Estimated tree height transects of the exposed fossilised tree stumps in fossil forest horizons SOA3 (a) and TA (b) within the Urawitiki Measures, Kawhia Harbour. The transects show the original Urawitiki Measures forests could well have had a multi-layered vertical structure. The width of the bars are approximately proportional to measured fossil stump diameter. The numbers capping the bars refer to fossil tree stump numbers (Appendix H).
shading\(^1\) and nutrient competition from the canopy and emergent trees. The shrubs may also not have been preserved or the random exposure line does not pass through many fossil shrub thickets. However, the preservation of a small number of shrub-sized stems indicates that preservation conditions were suitable. Further, the large number of fossil tree stumps intersected by the exposure line suggests that the probability of exposing a shrub stem would be high if they were part of the undergrowth. Therefore, significant shading and nutrient competition are considered the most plausible reason for a depleted undergrowth at this locality. The range of tree heights suggests that breaks in the canopy still allowed young trees to become established.

The lateral distribution of trees in fossil forests can only be determined from a fossilised tree stump horizon that is exposed parallel to the bedding plane providing information about the two-dimensional spacing of trees on the original forest floor. A suitable exposure was observed within fossilised tree stump horizon SOA2 in the Southern Ohanga Bay section, Te Maika Peninsula (Enclosures 4 and 9). The bedding surface, exposing 24 individual tree-sized fossil stumps, is exposed on a low sea-cliff due to the steep eastward dipping beds (38°097) (Figure 4.411). The mapped area of this exposure covers 102 m\(^2\) (17 m (north/south) x 6 m (vertically)) and the fossil tree stump distribution is illustrated in Figure 4.412. Table 4.14 summarises the structural data interpreted from this area of fossil forest floor including the basal area which is the total cross-sectional area of the fossil tree stumps.

\(^1\) Shading is an important aspect of the ecological situation, particularly in high latitude forests, and is discussed in detail in Section 5.6 with reference to net wood productivity.
Figure 4.411 Photograph of the two-dimensional exposure of fossilised forest floor (horizon SOA2) on a low sea-cliff in the Southern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour.

Figure 4.412 Lateral distribution of the fossilised tree stumps exposed over 102 m² of horizon SOA2, Southern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. Plan view. Each infilled circle represents the exact location of a fossilised stump and is proportional to its measured diameter. The numbers refer to the fossil stump numbers as mapped and the letters to taxa: B = Protocupressinoxylon sp. A; C = Podocarpoxylon sp. A (Appendix H). A-A’ represents the transect of estimated tree heights illustrated in Figure 4.413.
Table 4.14 Structural data for the two-dimensional exposure of fossilised tree stump horizon SOA2, Southern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour; m = metres, ha = hectare.

<table>
<thead>
<tr>
<th>Structural Parameter</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area mapped (m²)</td>
<td>102</td>
</tr>
<tr>
<td>Total number of trees:</td>
<td>24</td>
</tr>
<tr>
<td>(stem diameter ≥ 0.08 m)</td>
<td></td>
</tr>
<tr>
<td>Tree density: (trees/ha)</td>
<td>2353</td>
</tr>
<tr>
<td>Basal area: (m²/ha)</td>
<td>146</td>
</tr>
<tr>
<td>Trunk diameter (m):</td>
<td>(0.12) 0.26 (0.62)</td>
</tr>
<tr>
<td>(minimum) mean (maximum)</td>
<td></td>
</tr>
<tr>
<td>Estimated tree height (m):</td>
<td>(5.9) 9.5 (17.5)</td>
</tr>
<tr>
<td>(minimum) mean (maximum)</td>
<td></td>
</tr>
</tbody>
</table>

The original tree density in the patch of forest represented by the mapped area was high with a mean distance of only 1.78 m (standard deviation = 0.96 m) between the fossil stumps. Tree density is a subjective measurement, but the fossil stump spacing implies that the trees were growing close to each other and that the crowns could well have overlapped causing the canopy to be closed. Direct light would not have penetrated the canopy to the forest floor in this situation which could well explain the low proportion of shrub-sized stems within the SOA2 horizon and the remainder of the Urawitiki Measures fossil forest horizons. The estimated tree heights for the mapped area imply a similar vertical structure to the SOA3 and TA horizon transects (Figure 4.410) with a canopy between 5 and 10 m and scattered emergents rising to heights of up to 17.5 m (Figure 4.413). The fossil wood was well enough preserved in only 6 of the fossil stumps within the mapped area and identified as *Protocupressinoxylon* sp. A and *Podocarpoxyylon* sp. A (Figure 4.412; Section 4.23). The two taxa occur in equal proportions and are apparently randomly distributed.
Figure 4.413  North/south transect of estimated tree heights through the mapped area of horizon SOA2, Southern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour (Figure 4.412). Bar widths are approximately proportional to measured fossil stump diameter. Tree heights are estimated using Mosbrugger, et al.'s (1994) equation (refer to text for further explanation).

Curio Bay Fossil Forest Vertical and Lateral Structure

The in-growth-position fossilised stumps on the shore platform at Curio Bay are exposed approximately parallel to the fossil forest floor, so the original distribution can be studied over a wide area. Pole (pers. commun., 1997) mapped 2137 m² of the shore platform (Figure 4.414) using a 50 m baseline and a 5 m² quadrat and estimates that this
Figure 4.414 The area (2137 m²) of fossil forest floor on the shore platform at Curio Bay, Southland, mapped by Pole (pers. commun., 1997). Dots represent a selection of the fossilised stumps. Grid squares A8 to D-2 are analysed in this study. Locality of grid on shore platform is related to large base stumps (Pole, 1999).
area covers less than 25% of the exposed fossil forest floor. Within this area he recorded 182 tree-sized fossil stumps, 477 shrub-sized fossil stumps and 23 fossil tree-fern stumps.

Fossil stumps with a diffuse outer boundary could not be measured, which totalled 40 in number. The following analysis is based on fossil stump diameter data provided by Pole (pers. commun., 1997) for a portion of the mapped area which covers 975 m² of the shore platform (Figures 4.414 and 4.415). Figure 4.415 presents the distribution of tree-sized fossil stumps (approximately proportional to diameter) over this area and Figure 4.416 presents the fossil tree stump size frequency. Table 4.15 summarises structural data interpreted from this area of the fossil forest exposed at Curio Bay.

![Diagram](image_url)

**Figure 4.415** Lateral distribution of the fossilised tree (infilled black circles), shrub (dots) and tree-fern (crosses) stumps exposed over 975 m² of the fossil forest floor on the shore platform at Curio Bay, Southland. Plan view. Each infilled black circle is approximately proportional to the measured fossilised tree stump diameter (Table H6, Appendix H). B-B' represents the transect of estimated tree heights illustrated in Figure 4.417. Data after Pole, pers. commun., 1997).
Figure 4.416 A graph to indicate fossilised stump diameter frequency (including measurable shrub-sized stumps) within the area of the fossil forest floor horizon on the shore platform shown in Figure 4.415, Curio Bay, Southland. Data after Pole (pers. commun., 1997).

Table 4.15 Structural data for the two-dimensional exposure of fossilised tree stumps on the shore platform of Curio Bay, Southland; m = metres, ha = hectare.

<table>
<thead>
<tr>
<th>Structural Parameter</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area mapped (m²)</td>
<td>975</td>
</tr>
<tr>
<td>Total number of trees:</td>
<td></td>
</tr>
<tr>
<td>(stem diameter ≥0.08 m)</td>
<td>90</td>
</tr>
<tr>
<td>Tree density: (trees/ha)</td>
<td>923</td>
</tr>
<tr>
<td>Basal area: (m²/ha)</td>
<td>18.8</td>
</tr>
<tr>
<td>Trunk diameter (m):</td>
<td>(0.08) 0.13 (0.64)</td>
</tr>
<tr>
<td>(minimum) mean (maximum)</td>
<td></td>
</tr>
<tr>
<td>Estimated tree height (m):</td>
<td>(4.5) 6.0 (17.9)</td>
</tr>
<tr>
<td>(minimum) mean (maximum)</td>
<td></td>
</tr>
</tbody>
</table>

Within the mapped 975 m² of fossil forest floor, 366 fossil stumps were mapped of which 75% are shrub-sized stems of <0.08 m diameter indicating a substantial undergrowth with rare tree-ferns (Table H6, Appendix H). The majority of tree height estimates (83%) are between 1 and 5 m forming a shrubby low canopy beneath rare protruding trees up to 17.9 m tall. Pole's (1999) amended tree height estimates are double the figures quoted here (p. 284), but to compare the structure with the Kawhia
Harbour Temaikan forest, the original Mosbrugger, et. al (1994) equation is applied to Pole’s (pers. commun., 1997) Curio Bay data.

Figure 4.417 presents a shrub/tree height transect through the 975 m² area under investigation at Curio Bay (Figure 4.415) which illustrates the low canopy level and emergent trees. The trees are widely spaced compared to the Urawitiki Measures SOA2 horizon transect (Figure 4.413), despite Pole (1999) stating they appear “close-growing”. Widely spaced emergent trees above the canopy could well have allowed direct light to penetrate to the forest floor aiding the development of the substantial shrub and herbaceous layer. Therefore, the Curio Bay fossil forest deposit represents open shrubby woodland growth during the Temaikan rather than the closely spaced trees of the Kawhia Harbour forest. Colloquially, the terms *forest* and *woodland* are often used interchangeably. For continuity in this study, the Curio Bay fossil flora will continue to be referred to as a fossil *forest*.
Figure 4.417 Approximate west/east transect of estimated tree heights through the mapped area (Figure 4.415) of the fossil forest floor exposed on the shore platform at Curio Bay, Southland. Bar widths are approximately proportional to measured fossilised stump diameters. Tree heights are estimated using Mosbrugger, et al.’s (1994) equation (refer to text for further explanation). Data after Pole (pers. commun., 1997), Table H6, Appendix H.

4.45 Vegetation Palaeoprofile

A vegetation palaeoprofile is the modelling of plant communities from the geological record, on a much smaller scale than a plant association (Section 4.42), which grade in to each other with slight changes in habitat. Recognising vegetation palaeoprofiles within a fossil plant association can only be interpreted indirectly from a palynocenosis. For example, to investigate the co-habitation of the major plant groups in the Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour, the diversity or number of
taxa assigned to each group within each palynocenosis was counted (Figure 4.418). The results show no significant or consistent relationships between the natural taxonomic groups (for example, a consistent increase in one group on the decrease of another) throughout the stratigraphically successive palynocenoses (Figure 4.418). However, in general, the diversity of Filicopsida taxa appears to be inversely proportional to the Gymnospermopsida taxa. Further, the Fungi, Bryophyta and Lycopsida spores have a comparatively low diversity, but occur throughout the samples.

Figure 4.419 illustrates the proportion of dominant taxa grains and the total proportion of grains representing each major taxonomic group from palynocenoses within the Northern Ohanga Bay section, Te Maika Peninsula. Despite the limitations of quantitative analysis for Mesozoic palynocenoses (p. 261-262), consistent relationships between the proportions of the taxonomic groups can be seen. For example, the inverse relationship recognised from taxa diversity between the Filicopsida and Gymnospermopsida is reflected in their total relative grain abundance. In addition, *Araucariacites* spp. pollen is dominant in all the assemblages and has an approximately inverse relationship with the proportion of *Cycadopites* spp. pollen. The proportion of

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1 Sample VP959 from the Northern Ohanga Bay section (Figure 4.41) is not included in the following analysis due to a low grain count (Appendix G) rendering interpretation of taxa proportions statistically insignificant.
Figure 4.418 Diversity within the major taxonomic groups throughout stratigraphically successive palynocenoses from the Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. Diversity is measured as the proportion of taxa representing each taxonomic group within individual samples.
Figure 4.419  Relative abundance of the major taxa present in each stratigraphically successive palynocenosis from the Northern Ohanga Bay section, Te Maika Peninsula, Kawhia Harbour. The plot includes taxa with >5% abundance in at least one sample and the total proportion represented by each major taxonomic group per palynocenosis.
Cycadopites spp. is also high when there is a high proportion of Filicopsida-related grains. The remaining Gymnospermopsida groups\(^1\) occur in low proportions and the Cheirolepidaceae are unrepresented in both of these sections (although are present in the West Coast and Opapaka Point sections, Te Maika Peninsula).

The varying palynomorph diversity (Figure 4.418) and relative grain abundance of the major taxonomic groups (Figure 4.419) between the stratigraphically successive palynocenoses in the Northern Ohanga Bay section, Te Maika Peninsula, allows an interpretation of the Temaikan vegetation succession at this locality. The addition of life form reconstructions (Section 4.43) and a depositional setting provide the basis for a visual vegetation palaeoprofile (Figure 4.420).

Facies analysis has established that the Temaikan vegetation at Kawhia Harbour colonised the sub-aerial portions of substantial, continually accumulating, interdistributary bars of a laterally extensive sandy braided river system. The vegetation palaeoprofile envisaged could well have applied to the transition in vegetation types up the side of a bar from saturated and frequently inundated sediment at the water’s edge up to the higher, drier central area of the bar. In a braiding river environment, the bars shift position relatively rapidly. With the advent of major floods, the vegetated tops of

\(^1\) Only Corystospermaceae is represented in Figure 4.419 by Alisporites similis (Balme) Dettmann, 1963 and Alisporites spp. taxa.
<table>
<thead>
<tr>
<th>River Channel</th>
<th>Decreasing soil moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zone 1</td>
</tr>
<tr>
<td></td>
<td>Zone 2</td>
</tr>
<tr>
<td></td>
<td>Zone 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key:</th>
<th>Zone 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fungi</td>
<td>Bryophyta, Lycopsida (Isoetales and Lycopodiales), Fungi, Chlorophyta.</td>
</tr>
<tr>
<td>Bryophyta</td>
<td></td>
</tr>
<tr>
<td>Isoetales</td>
<td></td>
</tr>
<tr>
<td>Lycopodiales</td>
<td></td>
</tr>
<tr>
<td>Filicopsida:</td>
<td></td>
</tr>
<tr>
<td>Arborescent (tree-ferns)</td>
<td>Cupressaceae</td>
</tr>
<tr>
<td>Herbaceous (Filicales)</td>
<td>Podocarpacea</td>
</tr>
<tr>
<td>Gymnospermopsida: Caytoniaceae</td>
<td>Taxodiaceae</td>
</tr>
<tr>
<td>Caytoniaceae</td>
<td></td>
</tr>
<tr>
<td>Corystospermaceae</td>
<td>Cycadales</td>
</tr>
</tbody>
</table>

*Figure 4.420* Vegetation palaeoprofile model for the uppermost Urawitiki Measures fossil forests, Kawhia Harbour. Classification scheme after Stewart and Rothwell, 1993. Plant life form reconstructions after Francis, 1983; Stewart and Rothwell, 1993 and the author’s own based on modern examples (discussed in Section 4.43). Height of trees is not to scale. Zone components listed in approximate order of dominance.
even the most substantial bars would have been inundated approximately every 100-150 years (p. 134). However, this would be a minimum amount of time between devastating flood events to allow for the establishment of a mature stand of trees. The success of a tree-dominated vegetation in this depositional environment suggests that the new sediment surfaces were colonised rapidly before the next inundation. Similar soil moisture conditions on flood water drainage could well have meant vegetation colonisation would have occurred in the same sequence as the bar slope vegetation palaeoprofile. Three separate zones are recognised within the palaeoprofile (Figure 4.420).

**Zone 1**

Herbaceous plants adapted to living on wet or moist substrates (dominated by the bryophytes and lycopods) could have grown at the base of the palaeoprofile on frequently inundated sediment bordering the river channels. Fungi could also have grown in this zone on the damp sediment surface and dead vegetation. Aquatic lycopods (the Isoetales) and freshwater algae may have lined the river channels and grown in remnant bar top pools.

**Zone 2**

Beyond the saturated zone near the water’s edge, slightly higher up the bar, the edaphic conditions could well have been favourable for fern growth. The majority of extant ferns grow in damp environments, so it is assumed that the Jurassic relatives would have taken advantage of the same environmental conditions. The fern flora includes both
herbaceous and arborescent forms, so a canopy began to develop, causing partial shading of the low-level plants. Associated with the ferns in the macroflora are *Taeniopteris daintreei* McCoy, 1874 leaves suggesting the co-habitation of cycad trees in this zone. In the microflora, *Cycadopites* spp. pollen, that have an uncertain affinity to the cycads, are abundant in samples where there is also an abundance of Filicopsida spores and a noticeably lower proportion of Gymnospermopsida pollen (Figure 4.419). Over-representation of the *Cycadopites* spp. grains may be occurring (for example, a cycad tree could well have been close to the sample site), but this trend is repeated throughout the Ohanga Bay sections on Te Maika Peninsula. The decline in *Araucariacites* spp. pollen, in particular, coincides with an increase in *Cycadopites* spp. pollen, which could well be a true reflection of different habitat preferences. Fungi, bryophytes and lycopods continue to grow on the damp surface beneath the canopy.

**Zone 3**

On the central parts of the bar tops the sandy sediment surface, above the level of the river water, could well have been well-drained allowing the establishment of arborescent gymnosperms and a substantial canopy (interpreted to be between 5 and 10 m, Section 4.44) on primitive soils (p. 130). The consistent high abundance of Araucariaceae- and Corystospermaeae-affinity grains in the palynocenoses suggests these Gymnospermopsida families were co-habitants in this zone and common components of the forest¹. The single group of in-growth-position fossil tree-fern rhizome stumps in

¹ Again, there may be an unknown factor of over-representation involved in the abundance of grains of these groups, but this interpretation is reasonable considering the consistency of the relationship throughout the Ohanga Bay sections, Te Maika Peninsula.
fossil tree stump horizon JC1 (Jetty section, Te Maika Peninsula) suggests rare tree-ferns still grew on the well-drained substrate and could well have contributed to the canopy. Rare emergent gymnosperm trees protruded out of the canopy up to heights of 25.6 m (p. 285). Fungi, bryophyte and lycopod spores are also found in samples with high relative gymnosperm pollen abundance which could well have been growing on the damp forest floor, on trees or transported in from the forest margin. Chlorophyta spores were also observed in assemblages with abundant Gymnospermpopsida grains which suggests that freshwater algae may have been growing in bar top pools amongst the trees.

In summary, the palaeoprofile of the Urawitiki Measures forest could well have consisted of three plant zones. The forest of mixed Caytoniales and Coniferales affinity trees with a well-developed canopy and rare emergents could well have been surrounded by a zone dominated by herbaceous and arborescent ferns and cycad trees. The undergrowth could well have consisted of a community of fungi, bryophytes and lycopods on the moist forest floor.

The depositional environment for the Curio Bay fossil forest is considered to be a meandering river system, suggesting that the forest grew on levees and relatively level floodplains either side of a main river channel (Figure 2.35). The sandy palaeosols indicate the dominant sediment size that was transported by the river during flood stage and the silts could well have accumulated in the equivalent of ox-bow lakes on the floodplains. Therefore, the Curio Bay vegetation palaeoprofile could well represent vegetation growth from the saturated sediments at the river bank to the well-drained
periphery of the floodplain near the valley sides. Vegetation could also have recolonised a new flood-deposited sediment surface in a similar sequence. The recurrence interval of floods of a magnitude that would inundate and destroy the whole forest could well have occurred as frequently as at Kawhia Harbour due to the primitive palaeosols, but there is no other evidence available to support this hypothesis.

The small number of palynocenoses from the stratigraphic section at Curio Bay allows only broad interpretations about the source vegetation and comparisons with the Kawhia Harbour Temaikan forest. However, the Curio Bay forest had many similar plant components to the Urawitiki Measures forest (Section 4.42), and could well have had similar relationships between the natural taxonomic groups represented. Therefore, the vegetation palaeoprofile is envisaged to have had similar plant zones in response to similar soil moisture conditions to that of the Urawitiki Measures forest (Figure 4.42). Minor changes in the taxonomic composition of the Curio Bay fossil flora compared to that at Kawhia Harbour are presented as different life forms in the palaeoprofile. For example, the Curio Bay flora (either collected for this study or previously described) included no fossil representatives of Gleicheniaceae-related ferns or Cupressaceae-related gymnosperms. However, natural taxonomic groups that were present in addition to those observed at Kawhia Harbour include the Equisetales, Marattiales, Cycadeoidales and Pentoxylales.
Figure 4.421 Vegetation palaeoprofile model for the Curio Bay fossil forest. Classification scheme after Stewart and Rothwell, 1993. Plant life form reconstructions after Francis, 1983; Stewart and Rothwell, 1993 and the author's own based on modern examples (discussed in Section 4.43). Height of trees is not to scale. Zone components listed in approximate order of dominance.
Zone 1 in the Curio Bay vegetation palaeoprofile could well have been similar in composition to the Kawhia Harbour palaeoprofile; dominated by Bryophyta, Lycopodiales and Fungi with Chlorophyta living at the water’s edge. In addition, Isoetales and Equisetales could well have colonised this zone with its damp or saturated substrate.

Zone 2, on a moderately damp substrate, could well have been dominated by fern growth. Osmundaceae and Dicksoniaceae/Cyatheaceae relatives were arborescent in form, but in the herbaceous fern flora the Gleicheniaceae of the Kawhia Harbour forest were replaced by the Marattiales (but not necessarily occupying the same ecological niche). Members of the Hymenophyllaceae and Matoniaceae/Dipteridaceae/Chiropleuriaceae were also present in the herbaceous fern flora. The co-habitation of the Cycadales and ferns interpreted from the Urawitiki Measures flora could well have occurred in the Curio Bay forest, with the possible addition of the Cycadeoidales, although the preference of this group for a fern-dominated (Zone 2) or a gymnosperm-dominated (Zone 3) habitat is unknown. Bryophyta, Lycopodiales and Fungi continue to grow on the forest floor in this zone.

Zone 3 on a relatively well-drained substrate was dominated by the arborescent gymnosperms with a canopy developed between 1 and 5 m. The Araucariaceae and Podocarpaceae composed the dominant trees and shrubs. The Caytoniaceae, Corystosperrnaceae, Cheirolepidaeae and Taxodiaceae grew in minor amounts, but no Cupressaceae were present. The Pentoxylales also occur in the fossilised tree stump
flora of Curio Bay (Pole, 1988), representing an additional group in this zone not recorded during the collection for this study. Bryophyta, Lycopodiales and Fungi continue to grow on the forest floor beneath the canopy.

4.46 Summary

An analysis of the common occurrence of taxa in stratigraphically and laterally successive autochthonous palynomorph samples from the uppermost Urawitiki Measures at Kawhia Harbour implies that the flora preserved in the fossil forest beds was derived from the same Temaikan plant association. The fossil microflora from the lower Urawitiki Measures is also interpreted as being sourced from the same association, but from a wider catchment area. The Urawitiki Measures plant association grew on the sandy interdistributary bar tops of a braided river system which covered an area at least 4 km in width in the Kawhia Harbour region. Despite the common taxa between the Kawhia Harbour and Curio Bay fossil microfloral assemblages, the latter is interpreted to have been derived from a different plant association (possibly two separate associations). A different source association is expected due to the slightly younger age of the Curio Bay deposit and the different palaeogeographical locations.

Life form and forest structure analyses imply a multi-layered structure to the Temaikan vegetation with herbaceous, shrubby and arborescent plant life forms. Analysis of two-dimensional exposures of a single fossil forest floor revealed dense Temaikan forests at Kawhia Harbour and a correspondingly low shrub-sized stem abundance. In contrast,
the vegetation at Curio Bay was dominated by shrub-sized plants and rare, widely spaced trees. The canopy level in the forest at Kawhia Harbour was high at between 5 and 10 m with emergent trees protruding above the canopy and reaching up to 25.6 m. At the Curio Bay forest, the canopy was much lower, at between 1 and 5 m, but rare trees reached up to 17.9 m.

A vegetation palaeoprofile is constructed for both localities indicating the occurrence of plant successions related to soil moisture, from herbaceous hydrophilous plants at the river's edge to trees preferring a well-drained substrate at the interdistributary bar tops (Kawhia Harbour) or valley side beyond the floodplain (Curio Bay).

4.5 SUMMARY

Reconstruction of the early-mid Temaikan vegetation cover in the Kawhia Harbour and Curio Bay region has involved studies on the taxonomic composition, natural affinities, original life forms, vertical structure and distribution of the fossil flora. In addition, models of the transition of plant communities have been proposed in relation to the abiotic environment for each locality.

The diverse fossil flora collected and observed from the Temaikan strata at both Kawhia Harbour and Curio Bay includes many different types of dispersed organs, including three previously undescribed morphotypes of fossil trunk or stump wood with
Araucariaceae, Cupressaceae and Podocarpaceae affinities. Overall, the fossil macroflora and microflora record represents organisms from the Fungi, Protista (Chlorophyta) and Plantae Kingdoms. Remains from the Plantae Kingdom are the most diverse with dispersed organs related to the Bryophyta, Lycopsida (2 Orders, 1 Family), Equisetales (1 Order, 1 Family), Filicopsida (2 Orders, 5 Families) and Gymnospermopsida (4 Orders, 7 Families).

A taphonomic study of the fossil plant remains at Kawhia Harbour interpreted four taphocenoses within the Urawitiki Measures. All four taphocenoses contained allochthonous fossil plant material, but autochthonous remains, consisting of fossilised tree stumps still in growth position, leaves, spores and pollen (see discussion, pp. 259-260), only occurred in Taphocenoses 3 and 4 from the uppermost strata. The autochthonous remains are interpreted to represent an area of source vegetation in the Temaikan up to approximately 30 000 m² in extent (equivalent to ~174 x 174 m).

Analysis of common taxa within the palynocenoses implies that the spores and pollen preserved throughout the Urawitiki Measures samples had all originated from one plant association. Therefore, a single adaptive zone of relatively uniform depositional and environmental conditions covered at least the area of Urawitiki Measures exposure from Te Maika to Totara Peninsula in Kawhia Harbour. Facies and taphonomy analyses suggest that the vegetation at this locality grew on sub-aerial interdistributary bar tops on an extensive sandy braidplain. The Curio Bay fossil flora could well have been derived
from two plant associations (Section 4.42), which graded into each other across the floodplain of a meandering river.

The nature of the vegetation during the Temaikan at both Kawhia Harbour and Curio Bay is visualised by reconstructing life forms of the source plants. A lack of suitable dispersed organs within the beds sampled at Kawhia Harbour and poorly preserved material at Curio Bay requires that each plant group be represented by a life form based on previous reconstructions from the fossil record or on the habits of extant relatives. The life forms interpreted for the Temaikan flora include herbaceous, shrubby and arborescent habits and are broadly related to soil-moisture tolerance. For example, the herbaceous forms include the bryophytes, lycopods and ferns, the extant relatives of which are adapted to varying amounts of soil moisture; the fossil relatives of the Isoetales may even have been aquatic. In contrast, the presence of deeply penetrating tap roots (Figure 2.227), the lack of stump bulges or buttressing (p. 127) and growth from primitive sandy palaeosols implies the arborescent forms, dominated by gymnosperms, preferred well-drained soils.

The vertical structure of the source vegetation is estimated from the measured diameters of the in-growth-position fossilised tree stumps. The fossil forest at Kawhia Harbour consisted of predominantly arborescent plants forming a canopy between 5 and 10 m high. Rare emergent trees protrude above this level to heights of up to 25.6 m (outside the mapped area). In contrast, the Curio Bay fossil flora consisted predominantly of herbaceous and shrubby plants forming a low canopy between 1 and 5 m. Rare emergent
trees protruded up to 17.9 m. The range of heights indicated from the varying stump diameters at both localities suggests that the vegetation was actively regenerating when inundated by flood waters and had not reached the climax vegetative state in their respective environmental settings.

The distribution of plants over the forest floor is interpreted from the spacing of ingrowth-position stumps. A dense forest (2353 trees/ha) is interpreted for the Urawitiki Measures which would have prevented direct light reaching the forest floor. Total shading would explain the restricted shrubby undergrowth. Comparable structural parameters throughout individual stratigraphically successive fossilised tree stump horizons indicates that the depositional setting and environmental conditions remained similar throughout deposition of the uppermost Urawitiki Measures sediments. In contrast, the trees in the Curio Bay fossil forest were relatively widely spaced (923 trees/ha) with an open canopy. The open canopy would have allowed direct light to the forest floor and aided the development of a substantial ground and shrub layer.

Table 4.16 compares the density of the Temaikan forests of this study with other high palaeolatitude fossil forests and modern forests. The trees of the Urawitiki Measures forest are four to seven times denser than other high palaeolatitude fossil forest floors studied by previous authors, allowing virtually no light to penetrate to the forest floor. The Urawitiki Measures forest density compares most closely with modern day temperate broad-leaved or boreal needle-leaved forests in Canada (Loucks, et al., 1981). The forest density of the Curio Bay fossil forest is also high compared with other high
palaeolatitude forests, but is significantly less dense than the Kawhia Harbour fossil forest. The Curio Bay fossil forest density compares most closely with the average figure for modern freshwater riverine forests, which correlates with the depositional environment proposed for this forest.

The changes in interpreted life forms, diversity and abundance between stratigraphically successive palynocenoses imply successions in the plant communities within each association. The succession probably reflects plant growth progressing up the side of an interdistributary bar at Kawhia Harbour or vegetation growth across a floodplain at Curio Bay. At both sites, the palaeoprofile could also represent vegetation recolonising a new flood-deposited sediment surface. Three plant zones were interpreted for the Kawhia Harbour fossil forest which can also be applied, with minor compositional changes, to the Curio Bay fossil forest. The zones occur from saturated sediment conditions (dominated by Bryophyta, Lycopsida and Equisetales (the latter at Curio Bay only)), through a damp substrate zone (dominated by Filicopsida, Cycadales and possibly Cycadeoidales (the latter also found at Curio Bay only)) to a well-drained, primitive soil (dominated by Caytoniales and Coniferales).
Table 4.16  Tree density data from selected high palaeolatitude fossil forests and modern forests for comparison with the Temaikan forest densities from New Zealand.

<table>
<thead>
<tr>
<th>Location / Forest type</th>
<th>Author</th>
<th>Tree density (trees/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High palaeolatitude fossil forests</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kawhia Harbour, North Island, New Zealand (Middle Jurassic; palaeolatitude 75-78° South)</td>
<td>This thesis</td>
<td>2353</td>
</tr>
<tr>
<td>Curio Bay, South Island, New Zealand (Middle Jurassic; palaeolatitude 75-78° South)</td>
<td>This thesis; Pole (1999)</td>
<td>923</td>
</tr>
<tr>
<td>Alexander Island, Antarctic Peninsula (Lower Cretaceous; palaeolatitude 65-75° South)</td>
<td>Jefferson, 1982</td>
<td>588</td>
</tr>
<tr>
<td>Ellesmere Island, Arctic Canada (Eocene; palaeolatitude ~78° North)</td>
<td>Francis, 1988</td>
<td>367</td>
</tr>
<tr>
<td>Axel Heiberg Island, Arctic Canada (mid Eocene-early Oligocene; palaeolatitude ~78° North)</td>
<td>Francis, 1991</td>
<td>484, 325</td>
</tr>
<tr>
<td><strong>Modern forests</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spruce forests, Finland</td>
<td>Loucks, et al., 1981</td>
<td>485</td>
</tr>
<tr>
<td>Freshwater riverine forests</td>
<td>Brinson, in Lugo, et al., 1990</td>
<td>average 1076</td>
</tr>
<tr>
<td>Temperate broad-leaved evergreen forests</td>
<td>Loucks, et al., 1981</td>
<td>1000-3000</td>
</tr>
<tr>
<td>Boreal needle-leaved evergreen forests, Canada</td>
<td>Loucks, et al., 1981</td>
<td>&gt;3000</td>
</tr>
</tbody>
</table>
CHAPTER 5

VEGETATION DYNAMICS AND PALAEOCLIMATE

- FOSSIL WOOD GROWTH RING ANALYSIS

5.1 INTRODUCTION

Information on the forest environment, ecology and palaeoclimatic conditions within the vegetation source area can be interpreted from the analysis of growth rings observable in well-preserved fossil wood samples. An estimate of net wood productivity and biomass for the entire forest can also be calculated by extrapolating information about the modern high latitude light regime into the geological past. The formation and histology of growth rings is discussed in Section 4.23, but the final form of each individual ring depends on a variety of non-environmental as well as environmental influencing factors. The importance and effect of each factor on growth ring form must be recognised and understood before any interpretations can be made.

Non-environmental (or internal) factors which influence the appearance of growth rings include inheritable variation within species, age and changes in cellular size and proportion of earlywood (EW) and latewood (LW) depending on position within the tree (Figure 4.214). Environmental (or external) factors can be climate controlled and include water supply to the roots, atmospheric humidity, temperature (also related to
altitude), light, prevailing wind direction and overall stability of the climatic regime.

The site of growth may further influence growth patterns depending on the mineral nutrient supply from the substrate, aspect, slope and competition from neighbouring trees. In addition, biological pests and fire disrupt cell differentiation and alter the ring sequence (Chaloner and Creber, 1973). The effect of these influencing factors on the growth ring form includes varying ring or cell widths, differing numbers of cells within each ring, zones of frost damaged cells or an altered histological arrangement. Further, the influence of the external factors determines whether the tree will reach its genetic potential for growth. The above summary is based on thorough discussions on the influences on growth ring form in Creber and Chaloner (1984a; 1984b) to which the reader should refer for further details.

Chapman (1994) reviewed the features of fossil wood and limitations on their interpretation and compiled a list of characters considered useful for deriving palaeoclimatological interpretations. The list presented in Table 5.1 is abbreviated from the original to include only those features relevant to the study of the gymnospermous fossil wood material in this thesis. Relevant interpretations that can be drawn from the listed features are included in the table by the author.

The following section presents the results from a growth ring analysis, based on the characteristics listed in Table 5.1. Well-preserved samples of fossil wood are analysed from in-growth-position fossilised tree stumps exposed at Kawhia Harbour and *ex situ*
specimens from Kawhia Harbour\textsuperscript{1}, Slope Point (near Curio Bay) and Allan Hills, Antarctica. Late-early Permian fossil wood from Allan Hills represents a further example of high palaeolatitude gymnosperm growth and an analysis of the growth rings provides a useful comparison with the growth patterns of the Temaikan high latitude trees of New Zealand. The Allan Hills fossil wood is mainly of Glossopterid affinity, originally from the stump or trunk region and grew at approximately 80° South (Section 1.3; Francis, et al., 1994; Francis, pers. commun., 1997). The topics discussed are summarised in Table 5.2 and the laboratory methods described in Appendix E.

**Table 5.1** Characteristics of fossil wood and their uses in growth ring analysis for the interpretation of palaeoclimate; LW = latewood (adapted from Chapman, 1994).

<table>
<thead>
<tr>
<th><strong>Fossil Wood Characteristic</strong></th>
<th><strong>Interpretation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Part of tree sample originated from.</td>
<td>Recognition of the effect of tree structure on growth ring patterns.</td>
</tr>
<tr>
<td>Position in stem radius sample originated from.</td>
<td>Wider rings tend to occur in the centre of the trunk, than the periphery, due to rapid growth in the young tree.</td>
</tr>
<tr>
<td>Mean ring width.</td>
<td>General indication of vigour throughout a sequence of consecutive years.</td>
</tr>
<tr>
<td>Mean number of cells per ring.</td>
<td>Low numbers (&lt;10) indicate a stressed cambium and poor growing conditions. However, large numbers (&gt;30) indicate a rapidly dividing cambium and favourable growing conditions.</td>
</tr>
<tr>
<td>LW width and number of cells.</td>
<td>Can indicate the sample’s position within the tree (Figure 4.214), the photoperiodic response of the tree or the amount of rainfall at the end of the growing season.</td>
</tr>
<tr>
<td>Frost ring abundance, position and strength.</td>
<td>Predominantly indicates the severity and frequency of late frosts.</td>
</tr>
</tbody>
</table>

\textsuperscript{1}The in-growth-position and \textit{ex situ} samples from Kawhia Harbour are tabulated and figured separately as the author is only assuming that the \textit{ex situ} material is derived from the same strata.
Table 5.2  Growth ring analysis topics discussed in the following chapter.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 Growth Ring Description</td>
<td>Growth ring characteristics and their interpretations.</td>
</tr>
<tr>
<td>5.3 Growth Ring Classification</td>
<td>Recognition of ring types based on Creber and Chaloner (1984b). Ring classification aids the interpretation of changing environmental conditions during the growing season.</td>
</tr>
<tr>
<td>5.4 Growth Ring Widths</td>
<td>Growth ring width methods and results.</td>
</tr>
<tr>
<td>5.5 Tree Growth Patterns and Variability</td>
<td>Presentation and discussion of the measured growth ring sequences and an analysis of width variance using Annual Sensitivity.</td>
</tr>
<tr>
<td>5.6 Fossil Forest Productivity</td>
<td>Calculations of net wood productivity for individual trees using information on the light regime at 75° South. Biomass is also estimated from the growth ring width results for Kawhia and Slope Point near Curio Bay and applied to the entire Temaikan forest ecosystem.</td>
</tr>
<tr>
<td>5.7 Summary</td>
<td>A summary of the palaeoenvironmental, palaeoclimatic and palaeoecological interpretations from the growth ring analysis.</td>
</tr>
</tbody>
</table>

Despite the preservation of several laterally extensive fossilised tree stump horizons at Kawhia Harbour (Enclosures 8-10), dendrochronology was not attempted. To use tree rings for cross-dating purposes the trees must be sensitive to only one dominant environmental variable that limits growth, for example, precipitation or temperature and the annual ring produced must reflect the variation (Stokes and Smiley, 1968). It is also preferable to use healthy trees with long consecutive ring sequences. These influencing factors could only be assumed for the Mesozoic fossil wood. Therefore, the
inconsistencies of taphonomy and preservation in the Urawitiki Measures fossil forests negate the investigation of dendrochronology in this study.

5.2 GROWTH RING DESCRIPTION

All of the fossil wood samples studied from Kawhia Harbour, Slope Point near Curio Bay and Allan Hills exhibit growth rings of a similar form with very distinct boundaries (for example, Plates 9, 13 and Figure 5.21 respectively). The highly silicified fossil wood from Allan Hills commonly exhibited a zebra-striped effect with the LW appearing white and the EW black in colour (Figure 5.21(b)). Commonly the EW was highly distorted, so the black coloured zones were narrower than the original EW width. These distortions were accounted for using crush adjustment figures calculated for each sample (Figure E1, Appendix E). Fossil wood with distinct ring boundaries has been found in many high palaeolatitude fossil floras (for example, Schweitzer, 1980; Douglas and Williams, 1982; Jefferson, 1982; Francis, 1986, 1991).

All of the rings measured from the three study sites appeared to be true annual growth rings, with no gradational boundaries or damaged cells (other than due to patches of poor preservation) to suggest the occurrence of frost rings (p. 199). A lack of frost rings is typical in stump or base of trunk wood, which is not particularly susceptible to frost damage. However, frost rings were also not observed in the ex situ samples which could well have been derived from higher, more sensitive parts of the trunk. This evidence
Figure 5.21 Ex situ late-early Permian fossil wood from Allan Hills, Transantarctic Mountains, Antarctica.

(a) Transverse view of a fossil tree stump (not in growth position) showing distinct growth rings, an irregular outline characteristic of stump bases, departing roots (R) and a once hollow, now silica-infilled core (arrowed). Hammer = 32 cm long.

(b) Zebra-effect of growth ring preservation; LW = white, EW = black. Sample VH298. Scale on photograph.
suggests the trees were not affected by late frosts, implying either a growth site in the stable environment of the forest interior (for example, Francis, 1986) or a rapid rise in temperature at the beginning of each growing season (for example, Jefferson, 1982). Further, the lack of ‘frost’ rings suggests the forest was never affected by fire or insect attack (p.199).

Reaction wood (Jane, 1970) is also absent in all of the samples from all three study sites, which again is typical of stump or base of trunk wood. The formation of reaction wood causes bending of the trunk to maintain vertical growth on a sloping substrate or to maximise light interception. Although reaction wood is unusual in the trunk of a tree, its absence suggests that the topography at all three study sites was probably relatively level and that light was not limiting from any direction. Fossil wood from the Alexander Island fossil forests, west of the Antarctic Peninsula (Lower Cretaceous) contained abundant reaction wood which was interpreted as forming in response to tilting during flood events (Jefferson, 1982). However, the lack of reaction wood and the upright nature of the fossil tree stumps preserved in growth position at Kawhia Harbour and Curio Bay suggests that flood currents were generally not strong enough to tilt the trees.

The Kawhia Harbour and Allan Hills fossil wood samples consist of small tracheids (mean radial diameter up to 46.9 μm and 40.0 μm respectively; Tables IIa and IIb,

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1 This could be a result of the high ratio of diffuse to direct light common in the high latitudes (Warren Wilson, 1966).
Appendix I) compared to the size of cells measured from specimens of Cretaceous and Tertiary Antarctic wood (Francis, 1986) which reached up to ~65 μm in radial tracheid diameter. Tracheid cell size can vary significantly with position in the stem radius, for example, young wood in the centre of the stem has smaller tracheids than older wood nearer the stem periphery. The position of samples within the stem radius (inner or outer) was estimated from the curvature of the growth rings of the Kawhia Harbour specimens (Tables I1a and I1b, Appendix I). The ring measured from sample VH280 from Allan Hills was the last in the sequence (Table I2c, Appendix I) and from the outer stem radius. The position within the stem radius of the rings measured from Francis' (1986) collection is unknown.

There is little variation in tracheid cell size between *Araucarioxylon* sp., *Protocupressinoxylon* sp. A and *Podocarpxylon* sp. A, but *Protopodocarpxylon* sp. samples had comparatively wide tracheids and very high cell numbers per ring (Tables I1a and I1b, Appendix I). However, the wider tracheids may be due to the samples being derived from outer regions of the stem radius (except sample VH205) rather than specific genetic differences from the other taxa.
5.3 GROWTH RING CLASSIFICATION

Within an individual growth ring, the recognition of the position and nature of the boundary between the EW and LW zones can aid the interpretation of changing environmental conditions within a growing season. To analyse the EW and LW zones within a single ring the cumulative sum of deviations from the mean radial tracheid diameter (C.S.D.M.) is plotted against the cell number in the ring (Creber and Chaloner, 1984b). The point where the C.S.D.M. curve begins to trend to zero is identified as the location of the EW/LW boundary (Figure 5.31(a)). Using the position and nature (gradual or sharp) of the EW/LW boundary, Creber and Chaloner (1984b) recognised six different ring types from similar plots of rings from Upper Devonian to Lower Cretaceous fossil wood. More recently, a further ring type has been recognised from Permian wood from Allan Hills in Antarctica (Creber and Francis, 1999) and is referred to informally as ring type F in this study (Figure 5.31(b)).

The radial tracheid diameters of a single, undistorted radial file from several rings within uncrushed samples from Kawhia Harbour and from one ring in sample VH280 from Allan Hills were measured (Tables I2a to I2c, Appendix I). Cellular preservation is too poor in the Slope Point material to include in an investigation of ring type. The C.S.D.M. for these files of cells are plotted against tracheid number in the ring and are presented in Figures I1-I9, Appendix I. Where files from several rings in a sample were measured the ring with the most cells is plotted.
Figure 5.31 Growth ring types.
(a) A growth ring classification scheme showing six different recognisable growth ring types based on the position and nature of the EW/LW boundary. After Creber and Chaloner, 1984b.
(b) A new growth ring type found in Antarctic Permian wood from Allan Hills, Transantarctic Mountains, Antarctica; informally designated as ring type F in this study. Cell radial diameter curve and line of best fit is omitted. After Creber and Francis, 1999.
Several different ring types in the Kawhia Harbour fossil wood can be recognised from the EW/LW relationships following Creber and Chaloner’s (1984b) and Creber and Francis’ (1999) classification. Ring types recognised are summarised in Tables I3a to I3c, Appendix I. Ring types D and F are the most common and occur within all taxa except *Araucarioxyylon* sp. in approximately equal proportions (for example, Figure 5.32(a) and (b)). The *Araucarioxyylon* sp. sample (VH197) yielded a ring of type B, also observed in sample VH189 assigned to *Podocarposxylon* sp. A (Figure 5.33(a) and (b)). In addition, one sample assigned to *Podocarposxylon* sp. A exhibited ring type A (VH220, Figure 5.34).

Ring type D implies a growing season of relatively uniform conditions. The first formed EW cells increase in width rapidly and are then produced at approximately the same size for the majority of the season. Towards the end of the season, a terminal event occurs which causes the cessation of cambial activity after only a brief period of LW cell production (Figure 5.32(a)). In these rings, the EW/LW boundary is relatively sharp with a narrow LW zone. Fossil wood exhibiting the characteristics of ring type D is common throughout high palaeolatitude fossil floras (for example, Douglas and Williams, 1982; Jefferson, 1982; Francis, 1986). Ring type F is similar to ring type C (Figure 5.32(b) and Figure 5.31(a) respectively) and indicates gradually changing conditions throughout the growing season. The first formed EW cells are large, but decrease gradually in radial diameter throughout the duration of the growing season. The C.S.D.M. curve shows a gradual ascent to approximately the middle of the growing season and a similar graded descent to the end. In these rings, the EW and LW zones
Figure 5.32  Graphs to show examples of the most common growth ring types, D and F, observed in the Kawhia Harbour fossil wood (Protocupressinoxylon sp. A). For cell data refer to Tables I2a and I2b respectively, Appendix I.

(a)  In-growth-position, VH180, ring no. 75.
(b)  Ex situ, VH228, ring no. 2.
Figure 5.33  Graphs to show examples of growth ring type B, observed in the Kawhia Harbour fossil wood. For cell data refer to Table I2b, Appendix I.

(a)  *Araucarioxyylon* sp. (*ex situ*), VH197, ring no. 26.
(b)  *Podocarpoxyylon* sp. A (*ex situ*), VH189, ring no. 2.
are approximately equal, but the EW/LW boundaries are difficult to recognise without the aid of the C.S.D.M. plot.

Figure 5.34 An example of growth ring type A, observed in the Kawhia Harbour fossil wood. For cell data refer to Table 12b, Appendix I. *Podocarpxylon* sp. A (*ex situ*), VH220, ring no. 12.

The growth pattern of ring type F is observed in the Kawhia Harbour (Figure 5.32(b)) and Allan Hills (Figure 5.35) fossil wood which were growing at similar high palaeolatitudes during the Middle Jurassic and late-early Permian respectively within a similar light regime. At the beginning of the high latitude growing season, the first few hours of daylight trigger the production of the first, wide EW cells which continue to be produced with decreasing diameter until the end of the growing season when total darkness resumes. The EW/LW boundary is diffuse and occurs approximately at the middle of the growing season.
Figure 5.35 Graph to show the changing cell diameter across a growth ring of type F from sample VH280, Allan Hills, Transantarctic Mountains, Antarctica. For cell data refer to Table 12c, Appendix I.

The production of LW cells requires an adequate water supply late in the growing season. Therefore, due to the relatively wide LW zone in rings of type F, it can be assumed that water was not limiting to growth at the end of the growing season in either the Kawhia Harbour or Allan Hills depositional environments.

The occurrence of both ring types D and F in the same taxa within the Kawhia Harbour fossil forest (Figures II to I8, Appendix I) suggests that the growth pattern during each growing season is predominantly externally rather than internally controlled. No repeatable pattern was observed of specific ring types occurring in samples from either the inner or outer zones of the original stem’s radius.
Many rings in the Kawhia Harbour fossil wood, of types D and F, showed irregularities in the C.S.D.M. curve during the early part of the growing season (for example, Figure 5.36). Explanations for disruptions in cell production include the occurrence of severe storms, following which the trees underwent a period of repair before resuming normal cell production or the suppression of growth due to a period of waterlogging following a flood. The lack of frost rings already discussed indicates that temperature was not limiting to growth early in the season, so shortages in water supply during this period in some years may also have caused disruptions to cell production. The occurrence of a ring type A in sample VH220 (Figure 5.34), with a very narrow EW zone, a sharp boundary and a wide LW zone, also suggests disruption early in the season, from which the tree did not recover that year. However, there is no direct evidence to suggest any of these explanations are preferable to explain periods of cell production disruption early in the Temaikan growing seasons.

The occurrence of two ring types within fossil wood of the same taxa implies a variation in environmental conditions between growing seasons. For example, ring types D and F formed in a single tree. The occurrence of ring type D could well represent a warmer and wetter season where EW cells were produced for much longer than during formation of a ring type F. A brief water shortage late in the season could well have triggered the production of a few LW cells forming a ring type D before cambial activity ceased for the year. In addition, there could well have been physiological differences between individual trees of the same taxa, causing varying cell production patterns. Interpretations of these patterns can only be subjective.
Figure 5.36 Graphs to show examples of growth ring types D and F, observed in the Kawhia Harbour fossil wood, with irregularities in the cell diameters during the first half of the growing season (arrowed). For cell data refer to Table I2a, Appendix I.

(a) *Protocupressinoxylon* sp. A (in-growth-position), VH244, ring no. 15.

(b) *Podocarpxylon* sp. A (*ex situ*), VH213, ring no. 9.
In summary, the predominance of both ring types D and F in the Kawhia Harbour fossil wood suggests a clearly defined growing season. At the beginning, the rapid onset of favourable temperature and water supply conditions triggered the production of wide EW cells, which were subsequently produced at either similar sizes during a particularly wet season (ring type D) or gradually declined in size throughout (ring type F). Local water shortages, severe storms or periods of waterlogging affected EW cell production in several trees during the first half of the growing seasons of some years, but none appeared to affect growth in the latter half.

The annual cell production patterns and distinct ring boundaries indicate a clearly delineated growing season occurred during the Middle Jurassic. Although independent of the assumption that New Zealand occupied high palaeolatitudes during this period, the form of the growth rings is highly comparable to that of the high palaeolatitude late-early Permian growth which also suggests the occurrence of a distinct growing season. Assuming a high New Zealand palaeolatitude, the respective increasing and decreasing of near-polar photoperiod at the beginning and end of the season probably acted as the trigger for the onset of photosynthesis (as soon as the temperature was high enough for growth\(^1\)). Cambial activity would have reached a maximum during the short period of 24 hour daylight in the middle of the season. Temperatures were warm enough to allow growth throughout the growing season with no interruptions due to late frosts.

\(^1\) The growth process for many plant species begins at 6\(^\circ\)C (Jones, 1979).
5.4 GROWTH RING WIDTHS

Consecutive growth ring sequences have been measured from fossil wood specimens collected from the Temaikan of Kawhia Harbour and Slope Point near Curio Bay and also the late-early Permian of Allan Hills. Methods of growth ring width measurement are outlined in Appendix E. Growth ring sequences from Kawhia Harbour fossil wood were measured from 22 samples collected from in-growth-position tree stumps and 44 ex situ samples (Tables I4a and I4b, Appendix I). The majority of the ex situ material was found on the west coast of Totara Peninsula. Enclosures 8-10 illustrate which in-growth-position fossilised tree stumps were sampled. At Slope Point, four samples derived from sediments approximately coeval to the Curio Bay fossil forest deposit yielded measurable ring sequences, but the remaining nine were too distorted (Table I4c, Appendix I). Twenty-four fossil wood samples collected from ex situ material derived from the Weller Coal Measures at Allan Hills yielded measurable sequences (Table I4d, Appendix I).

Due to fracturing on collection of fossil wood from Kawhia Harbour and large patches of poor preservation, two or three separate ring sequences were recorded from different parts of the stem radius in eleven samples. Of these multiple sequences, only the longest sequence (with the highest number of consecutive rings counted) is used for variation analysis (Section 5.5) to ensure the results are representative of the tree’s growth patterns over as many years of its life as possible (Tables I4a and I4b, Appendix I). However, all
of the rings measured were included in the maximum, minimum and mean growth ring width statistics (summarised in Tables I5a and I5b, Appendix I).

Table 5.3 summarises the growth ring width results from the Kawhia Harbour, Slope Point near Curio Bay and the Allan Hills fossil wood collections. Mean growth ring width values are highly dependant on the location of the sample within the original stem's radius as sequences measured from the inner stem tend to reflect vigorous growth of a young tree and the rings towards the outer radius become narrower as the tree ages.

Fossil wood from Kawhia Harbour shows considerable variation within and between taxa. However, Protopodocarpoxylon sp. samples generally exhibit much wider growth rings than the other taxa (for example, Plate 23, Figure 3,4). This taxa is also distinct by

Table 5.3 Fossil wood growth ring width results for samples from the Temaikan of Kawhia Harbour and Slope Point near Curio Bay, New Zealand and the late-early Permian of Allan Hills, Antarctica.

<table>
<thead>
<tr>
<th>Study site</th>
<th>No. of samples measured</th>
<th>Mean ring width range (mm)</th>
<th>Minimum ring width (mm)</th>
<th>Maximum ring width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kawhia Harbour</td>
<td>66</td>
<td>0.03-4.91</td>
<td>0.03</td>
<td>9.67</td>
</tr>
<tr>
<td>Slope Point near Curio Bay</td>
<td>4</td>
<td>0.77-2.89</td>
<td>0.29</td>
<td>5.67</td>
</tr>
<tr>
<td>Allan Hills</td>
<td>25</td>
<td>0.76-11.00</td>
<td>0.21</td>
<td>19.05</td>
</tr>
</tbody>
</table>

the larger size of its tracheids (Section 5.2) which suggests that internal factors could well have more of an influence on the growth ring patterns than in the other taxa studied. The Slope Point fossil wood has a narrower mean ring width range, within that exhibited
by the Kawhia Harbour material of a similar age. However, a larger collection of fossil wood is required from the Southland Temaikan to be able to study ring width characteristics from that location adequately.

The Allan Hills fossil wood exhibited several extremely wide rings, indicating a much faster growth rate than the Temaikan fossil wood when conditions were favourable (for example, Figure 5.41). Trees with similar growth rates have been observed in the late Permian Buckley Formation from Mt. Achernar in the Transantarctic Mountains (Table 5.4; Taylor, et al., 1992). Extremely wide growth rings could reflect several influences, including taxonomy, nutrient and water supply at the time of growth.

**Figure 5.41** Extremely wide growth rings in *ex situ* late-early Permian fossil wood, Allan Hills, Transantarctic Mountains, Antarctica. Arrowed growth ring is 11.00 mm wide. Sample VH276. Scale on photograph.
The growth ring widths from all three study sites compare well to that of other high palaeolatitude fossil wood of gymnospermous affinity (Table 5.4). The general similarity of the growth ring width characteristics, regardless of geological age, suggests similar responses by gymnosperm-related vegetation to the high palaeolatitude light regime in both hemispheres.

**Table 5.4** Growth ring width data from selected high palaeolatitude fossil wood.

<table>
<thead>
<tr>
<th>Location</th>
<th>Author</th>
<th>Natural affinity</th>
<th>Mean ring width range (mm)</th>
<th>Maximum ring width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axel Heiberg Island, Arctic Canada (mid Eocene-early Oligocene; palaeolatitude ~78° North)</td>
<td>Francis, 1991</td>
<td>Taxodiaceae</td>
<td>3.00</td>
<td>-</td>
</tr>
<tr>
<td>Antarctic Peninsula and South Shetland Islands (early Cretaceous-Eocene/early Oligocene; palaeolatitude &gt;60° South)</td>
<td>Francis, 1986</td>
<td>Podocarpaceae /Araucariaceae</td>
<td>0.52-5.57</td>
<td>9.00</td>
</tr>
<tr>
<td>Alexander Island, Antarctic Peninsula (Lower Cretaceous; palaeolatitude 65-75° South)</td>
<td>Jefferson, 1982</td>
<td>Gymnosperm (Araucariaceae /Cupressaceae)</td>
<td>0.40-3.58</td>
<td>9.55</td>
</tr>
<tr>
<td>Victoria, Australia (late Jurassic-earliest Cretaceous; palaeolatitude 70-85° South)</td>
<td>Douglas and Williams, 1982</td>
<td>Podocarpaceae /Araucariaceae</td>
<td>-</td>
<td>7.0</td>
</tr>
<tr>
<td>Mt. Achernar, Transantarctic Mountains (late Permian; palaeolatitude 80-85° South)</td>
<td>Taylor, et al., 1992</td>
<td>?Glossopterid</td>
<td>4.5</td>
<td>11.38</td>
</tr>
</tbody>
</table>
Compared to modern conifers at high southern and northern latitudes, the Temaikan and Permian fossil wood exhibit wider growth rings. For example, at 60° North in Leningrad, the widest growth ring recorded from Pinus sylvestris was 2.1 mm (Creber and Chaloner, 1984b). Cell production is mainly affected by temperature and light and the northern tree-line (~66° North) approximates the 10°C isotherm for July (Creber and Chaloner, 1984b). In the Southern Hemisphere the tree-line is at ~55° South, at the tip of South America which has a cold temperate climate. Araucaria araucara trees in Argentina (37-43° South) produce rings that are mainly <1 mm (LaMarche, et al., 1979a). The relatively wide ring widths of the Kawhia Harbour fossil wood compare well to Callitris conifers (Cupressaceae) in Queensland, Australia at 17° South (Ash, 1983; Francis, 1986) which recently produced rings up to 3-5 mm wide (mean = 2.5 mm). The climate is very warm and wet, but with a distinct dry season. The growth ring characteristics of the Temaikan and Permian fossil woods imply that adaptation by gymnosperm plants to the high latitude light regime was far more efficient in the geological past than it is now.

The estimation of tree ages from fossil tree stump diameters and mean growth ring widths in successive horizons was considered as a method of calculating the approximate recurrence interval of devastating floods in the Urawitiki Measures depositional environment at Kawhia Harbour. However, limitations including the accuracy of the fossil tree stump diameter measurement (affected by burial and fossilisation) and the location of the ring width sequence averaged within the stem radius rendered the investigation unrealistic.
5.5 TREE GROWTH PATTERNS AND VARIABILITY

5.51 Growth Ring Width Patterns

Consecutive sequences up to 95 growth rings long were measured from Kawhia Harbour, Slope Point and Allan Hills fossil wood samples (Tables I4a to I4d, Appendix I). Sequences greater than 20 consecutive rings are presented graphically in Figures I10-I20 (Appendix I) and are considered to provide a reasonable estimate of the growth patterns of the original tree. The growth response of trees to varying environmental conditions is regarded as being similar despite geological age, so the following interpretations include both the New Zealand Jurassic and the Antarctic Permian material studied. The majority of samples from all three study sites exhibit highly variable growth ring widths from year to year regardless of original position in the stems radius (for example, Figure 5.51).

Several samples from the inner stem exhibited the typical growth ring width pattern observed in the radius of a young tree, with generally wide (but commonly highly variable year to year) rings near to the core, narrowing and stabilising in width, year to year, as the tree becomes older (for example, Figure 5.52). However, some sequences exhibited narrower rings nearer the core gradually becoming wider throughout the life of the tree (for example, Figure 5.53). These samples may have been from trees that were restricted by environmental conditions during their early life which subsequently became more favourable allowing an increase in cell production. For example, the
Figure 5.51  Growth ring width graphs to indicate the general variability of growth ring widths from year to year in Kawhia Harbour ((a) to (c)) and Allan Hills (d) fossil wood. For ring width data refer to Tables I4a, I4b and I4d, Appendix I.

(a)  *Podocarpxylon* sp. A (in-growth-position), inner stem, VH173.
(b)  *Podocarpxylon* sp. A (in-growth-position), outer stem, VH188.
(c)  *Protopodocarpxylon* sp. (*ex situ*), outer stem, VH204.
(d)  *Gen. indet.* (*ex situ*), outer stem, VH281.
Figure 5.52 Growth ring width graphs to show sequences from Kawhia Harbour (a) to (c)) and Allan Hills, (d) fossil wood. These examples begin with wide, but variable, widths year to year, but become gradually narrower and more uniform as the tree ages. For ring width data refer to Tables I4a, I4b and I4d, Appendix I.

(a) Gen. indet. (in-growth-position), inner stem, VH135(a).
(b) Podocarpoxylon sp. A (ex situ), inner stem, VH217.
(c) Protocupressinoxylon sp. A (ex situ), inner stem, VH228.
(d) Gen. indet. (ex situ), outer stem, VH291.
Figure 5.53  Growth ring width graphs to show sequences from Kawhia Harbour fossil wood. These examples begin with generally narrower rings and end with wider rings in the older tree. For ring data refer to Table I4b, Appendix I.
(a)  *Protopodocarpoxyylon* sp. (*ex situ*), inner stem, VH205.
(b)  *Protocupressinoxylon* sp. A (*ex situ*), outer stem, VH235(b).
mature trees within the closed canopy of the Urawitiki Measures forest at Kawhia Harbour restricted light to the forest floor impairing the growth of younger trees. These growth conditions may be reflected in the growth ring sequences and also in the low abundance of shrub-sized stumps preserved within the fossil forest horizons (Section 4.44). Forest structure of the late-early Permian Weller Coal Measures is unknown due to the *ex situ* nature of the fossilised wood exposed. A further cause of growth impairment is waterlogging, but other than the major floods which destroyed each forest horizon at Kawhia Harbour, a lack of stump bulges imply there was no permanent standing water around the tree bases. In addition, the thin remnant leaf litter layers and the sandy, primitive soil would have drained easily.

Sequences within samples from the outer part of the stem exhibit similar periods of wide and narrow rings to the inner parts. In this more mature stage in the plant's life, the ring widths generally become relatively narrow and the different periods of dominantly wide or narrow ring widths reflect periods of favourable or unfavourable environmental conditions. For example, sample VH235 (Figure 5.53(b)) undergoes a relatively low period of production for many years during the first part of the sequence, but environmental conditions began improving from approximately year 28, causing a greater overall cell production in the following years. In contrast, sample VH280 (Figure 5.54(a)) from Allan Hills has a variable sequence of narrow width rings for approximately 85 years, then the penultimate ring in the sequence shows a growth rate 2-3 times faster than previous rates, indicating a sudden, rather than a gradual, improvement in palaeoenvironmental conditions.
Figure 5.54  Growth ring width graphs showing periods of both favourable and unfavourable environmental conditions throughout the life of the trees. Gen. indet. fossil wood from Allan Hills. For ring data refer to Table I4d, Appendix I.

(a)  Sample VH280 indicates a sudden improvement in conditions at the end of the measured sequence.

(b)  Sample VH279 shows a sudden deterioration in conditions towards the end of the sequence.
Parts of sequences with dominantly wide rings from the Kawhia Harbour fossil wood commonly show very variable ring width changes year to year. This probably reflects extreme climatic events, for example, alternating hot summers with extremely favourable growing conditions with summers that were cooler and perhaps had more frequent storms or droughts that would lessen the cell production for that season. Another period of slow growth rate, implying a period of poor growing conditions compared to the rest of the sequence can be seen in sample VH279 from Allan Hills (Figure 5.54(b)). This pattern was not seen in the majority of the Allan Hills fossil wood suggesting that the climatic pattern at the time of tree growth was more stable than in the New Zealand Tambaikan. Environmental conditions in one growing season can have a minor effect on the form of the growth ring in the next, so interpretations based on year to year changes can only be subjective.

Some fossil wood samples from the Urawitiki Measures may indicate cycles of particularly unfavourable growing seasons over a 4-6 and a ~20 year period (Figure 5.55), but due to the low number of long sequences (Jefferson (1982) only used sequences of >40 rings for periodicity analysis) further samples are needed to test these results. Cycles of 6-8 years can also be seen in two of the Allan Hills samples (Figure 5.56), but again, longer sequences and a larger data set are required for significant analysis. Jefferson (1982) recognised 2, 3 and 4 year periodicities in most of the early Cretaceous trees analysed from Alexander Island off the Antarctic Peninsula. He compared these to the biennial or triennial solar cycles (Schove, 1978) and also recognised a strong 11-12 year cycle in four of the trees which he suggested may be
Figure 5.55 Growth ring width graphs to show possible periodicity in the growth patterns of Kawhia Harbour fossil wood. Periods of slow growth (unfavourable growing seasons) are arrowed. For ring data refer to Table I4b, Appendix I.

Cycle of 4-6 years between particularly unfavourable growing seasons:
(a)  *Podocarpoxyylon* sp. A (*ex situ*), outer stem, VH189.
Possible ~20 year cycle:
(b)  *Protocupressinoxyylon* sp. A (*ex situ*), inner stem, VH224.
(c)  *Protocupressinoxyylon* sp. A (*ex situ*), outer stem, VH240.
Figure 5.56  Growth ring width graphs to show possible periodicity in the growth patterns of Allan Hills *Gen. indet.* fossil wood (*ex situ*). A cycle of 6-8 years between particularly unfavourable growing seasons can be observed in both sequences. Periods of slow growth (unfavourable growing seasons) are arrowed. For ring data refer to Table I4d, Appendix I.
(a) VH277, inner stem.
(b) VH286, outer stem.
controlled by sun-spot cycles. The tentative identification of cycles in fossil wood from the Kawhia Harbour trees correlates with the 4 year cycle recognised from the Alexander Island fossil wood, perhaps also linking Middle Jurassic tree-growth to solar cycles. The ~20 year cycle recognised in certain Kawhia Harbour fossil wood sequences does not appear to reflect solar activity cycles. However, nearby volcanic eruptions from the Temaikan arc on the Gondwanaland margin in this region (Section 1.32) may have been periodic and influenced growth ring widths. However, a much larger data set is required to test the periodicities quantitatively for significant interpretations.

5.52 Annual and Mean Sensitivity

Douglas (1928) devised a quantitative approach to measuring variability in growth ring sequences by calculating the Annual Sensitivity (A.S.) for two consecutive growth rings. Annual Sensitivity is defined as the difference in width between a pair of consecutive rings divided by their average width (Creber, 1977). The average A.S., or the Mean Sensitivity (M.S.) represents the tree’s response to an environmental variable that fluctuates significantly from year to year, for example, water supply. The M.S. is calculated using the following equation:

\[ MS = \frac{1}{n-1} \sum_{i=1}^{n-1} \left| \frac{2(x_{i+1} - x_i)}{x_{i+1} + x_i} \right| \]
where \( x \) is the ring width (mm), \( n \) is the number of rings and \( t \) is the year number of each ring. Mean Sensitivity values in living trees range from 0 to 1.0 (Douglas, 1928), but can reach a theoretical maximum value of 2.0 (Francis, 1986). Douglas (1928) described an arbitrary M.S. boundary at 0.3, below which the trees are regarded as *complacent* having grown in relatively uniform environmental or climatic conditions and show little variation in ring width from year to year. Above 0.3 the trees are considered *sensitive* where growth has responded to significantly varying environmental influences and ring widths are considerably different from year to year. The A.S. values are presented with the growth ring data from fossil wood at all three study sites in Tables I4a to I4d and M.S. values along with the complacent or sensitive interpretation are presented in Tables I6a and I6b (Appendix I). The low number of rings measured within certain sequences distorts the M.S. values for these trees, so only sequences with \( \geq 20 \) consecutive rings from all three study sites are considered to reflect original growth patterns.

Mean sensitivity values for both the in-growth-position and *ex situ* Kawhia Harbour fossil wood samples range from 0.09 to 0.58 with the majority lying between 0.2 and 0.39 (Table I6a and I6b, Appendix I). The range of M.S. in sequences of \( \geq 20 \) rings from all taxa is similar, between 0.12 and 0.53. Within separate taxa, approximately equal proportions of complacent and sensitive trees occur in the *Protocupressinoxylon* sp. A (complacent = 46\%, sensitive = 42\%, borderline = 12\%) and *Podocarpxylon* sp. A (complacent = 59\%, sensitive = 41\%, borderline = 0\%) samples. The ring sequences of *Protopodocarpxylon* sp. are dominantly complacent (5 out of 6 samples). Overall, the
Kawhia Harbour trees show dominantly complacent growth (57% of samples measured) with 35% showing sensitive growth patterns and 8% having borderline M.S. values.

The range of M.S. is similar throughout each taxa and from different locations within the original stem’s radius indicating that growth ring variability is generally not significantly affected by internal factors. Fossilised tree stumps still in growth position were more sensitive to environmental conditions in the Totara Peninsula section than in the Te Maika Peninsula sections at Kawhia Harbour. This suggests the location of a forest margin in the Totara Peninsula during the Temaikan, as environmental conditions within the forest interior are generally more stable than those on the periphery. However, the *ex situ* samples which we assume have also been derived from the Urawitiki Measures strata at Totara Peninsula show varying degrees of sensitivity (Table I6b, Appendix I). There are no patterns of M.S. change stratigraphically up the various fossil-forest-bearing horizons.

The percentage frequency of A.S. in selected growth ring sequences, from both *ex situ* and in-growth-position Kawhia Harbour fossil wood samples, are presented in Figures 5.57 and 5.58. These graphs indicate a range of A.S. values within each sequence, all showing a sensitive tail, even when the dominant growth pattern is complacent (for example, Figure 5.57(a) and Figure 5.58(a)). The examples shown in Figures 5.57 and 5.58 are representative of the remainder of the ring sequences measured.
Figure 5.57  Histograms to show the variability in percentage frequency of Annual Sensitivity (A.S.) values within three ring sequences measured from fossilised Protocupressinoxylon sp. A tree stumps preserved in-growth-position at Kawhia Harbour. For A.S. data refer to Table I4a, Appendix I. The dashed line represents the boundary between complacent (<0.3 A.S.) and sensitive (>0.3 A.S.) growth patterns. Arrow = Mean Sensitivity (see text for explanation).
(a) Complacent growth, VH180(b).
(b) Borderline complacent/sensitive growth, VH178.
(c) Sensitive growth, VH245(a).
Figure 5.58  Histograms to show the variability in percentage frequency of Annual Sensitivity (A.S.) values within three ring sequences measured from ex situ fossil wood samples from Kawhia Harbour. For A.S. data refer to Table I4b, Appendix I. The dashed line represents the boundary between complacent (<0.3 A.S.) and sensitive (>0.3 A.S.) growth patterns. Arrow = Mean Sensitivity (see text for explanation).

(a)  *Araucarioxylon* sp. - complacent growth, VH197.
(b)  *Protocupressinoxylon* sp. A - borderline complacent/sensitive growth, VH228.
(c)  *Protocupressinoxylon* sp. A, sensitive growth, VH224.
Mean Sensitivity values for Slope Point fossil wood samples\(^1\) are 0.26 and 0.38 (samples VH263 and VH274 respectively; Table I6c, Appendix I). The *Araucarioxylon* sp. A sample is complacent and the *Gen. indet.* sample sensitive. The small data set does not adequately reflect the response of the whole forest to environmental variables, but shows how individual trees, assumed to have been growing contemporaneously, react differently to the palaeoenvironment. The A.S. percentage frequency graphs for these samples (Figure 5.59) show the difference in sensitivity between the two taxa with *Araucarioxylon* sp. A exhibiting dominantly complacent growth with rare years when conditions, for example, water supply, varied significantly to affect cell production. In contrast, *Gen. indet.*, despite a relatively high proportion of complacent years growth, was sensitive, overall, to the fluctuations of an environmental variable.

Mean Sensitivity within the Allan Hills Permian fossil wood samples\(^2\) ranged between 0.14 and 0.33 (Table I6d, Appendix I). These trees showed predominately complacent growth patterns (67%) indicating that palaeoenvironmental conditions were generally favourable for growth year to year. Figure 5.510 presents A.S. percentage frequency graphs for three samples, all of which indicate dominantly complacent A.S. values with a sensitive tail.

\(^1\) For sequences ≥20 growth rings only.
\(^2\) For sequences ≥20 growth rings only.
Figure 5.59  Histograms to show the variability in percentage frequency of Annual Sensitivity (A.S.) values between the ex situ Slope Point (near Curio Bay) fossil trees. For A.S. data refer to Table I4c, Appendix I. The dashed line represents the boundary between complacent (<0.3 A.S.) and sensitive (>0.3 A.S.) growth patterns. Arrow = Mean Sensitivity (see text for explanation).
(a)  Araucarioxylon sp. A - complacent growth, VH263.
(b)  Gen. indet. - sensitive growth, VH274.
Figure 5.510 Histograms to show the dominantly complacent growth patterns within three ring sequences measured from *ex situ* *Gen. indet.* fossil wood samples from Allan Hills. For A.S. data refer to Table 14d, Appendix I. The dashed line represents the boundary between complacent (<0.3 A.S.) and sensitive (>0.3 A.S.) growth patterns. Arrow = Mean Sensitivity (see text for explanation).

(a) VH277.
(b) VH280.
(c) VH291.
Sensitive growth patterns in modern trees are commonly found in marginal environments where the tree is close to its ecological limit. The Temaikan forest at Kawhia Harbour, from sedimentological and palaeobotanical evidence, was growing in a humid environment, with no late frosts in the growing season, on a near-coastal braidplain of relatively level topography. A high proportion of the trees at this study site exhibit complacent growth patterns, but a significant number also have sensitive growth patterns. The mean and maximum ring widths vary, but are generally high at this locality with a maximum ring width of 9.67 mm and 8.17 mm from inner and outer stem samples respectively. This suggests that although the Temaikan Kawhia Harbour trees are assumed to have been growing at high palaeolatitudes (75-78° South), they were still capable of substantial growth within a favourable season.

The high proportions of complacent and sensitive growth patterns within taxa of the Kawhia Harbour fossil forest, implies that they are mainly externally controlled being influenced by local site conditions. For example, trees with a sensitive growth pattern may have been located on the edge of a clearing or at the forest margin where climatic variables, especially temperature, fluctuated sufficiently to influence the production of cells. Trees of the same taxa growing in the sheltered environment of the forest interior were protected by surrounding trees and could have shown complacent growth patterns.

The growth patterns of the Kawhia Harbour or Allan Hills trees do not compare well to either modern high latitude tree growth or to other high palaeolatitude fossil forest growth patterns. Trees at the sub-Arctic tree-line (between 60-70° North) exhibit low
mean and maximum ring widths and complacent growth, despite the marginal environment (Ording, 1941 (northern Norway); Giddings, 1943 (Alaska); Drew, 1975 (northern Canada)). The trees in this study show both sensitive and complacent growth with generally high mean and maximum ring widths.

Fossil gymnospermous wood from the Antarctic Peninsula and South Shetland Islands (early Cretaceous to Eocene/early Oligocene; palaeolatitude >60° South) also exhibits dominantly complacent growth patterns with M.S. values ranging between 0.125 and 0.267, with one sample reaching 0.371¹ (Francis, 1986). Jefferson’s (1982) trees exhibited generally high mean and maximum ring widths with consistently sensitive growth (M.S. = 0.326-0.739, with one sample complacent at 0.029²), overall, comparing well with the sensitive growth patterns of Phyllocladus trees in the warm temperate rainforest of southern New Zealand and Tasmania (ibid.).

The Kawhia Harbour fossil trees exhibit features in common with both modern high latitude gymnosperm growth and fossil forest data. For example, generally high mean and maximum ring widths suggest rapid growth in years of favourable climatic conditions. Further, both complacent and sensitive growth patterns may be due to the site of individual tree growth, rather than being species dependant. Therefore, the growth patterns suggest more favourable climatic conditions overall in the Kawhia

¹ Including sequences with <20 growth rings.
² Including sequences with <20 growth rings.
Harbour region during the Temaikan, allowing increased cell production compared to growth at the modern northern tree-line. Climatic variability also significantly affected the growth in trees at the forest margin during the Temaikan. These results are comparable to the interpretations made from the study of the growth ring width sequence graphs which suggest cyclic periods of favourable and unfavourable growing seasons.

The growth patterns of the Permian Allan Hills trees compare most closely with the early Cretaceous to Eocene/early Oligocene fossil wood from the Antarctic Peninsula and South Shetland Islands (Francis, 1986) with dominantly complacent growth patterns implying generally favourable environmental conditions year to year in the Gondwanaland continental interior.

5.6 FOSSIL FOREST PRODUCTIVITY

5.61 Introduction

Productivity can be defined as the amount of organic matter produced by photosynthetic plants, after respiration, incorporating energy from sunlight (Lieth and Whittaker, 1975) and is commonly expressed in tonnes per hectare per year for forest ecosystems (t/ha/y). Net wood productivity in gymnosperms is the amount of tracheid cells produced in one growing season and can be estimated for a particular year from the width of a growth
ring within the trunk of a tree. Therefore, the preservation of tree stumps in-growth-position within the uppermost Urawitiki Measures strata of Kawhia Harbour allows an estimation of the net wood productivity of the Temaikan forests. Assuming a high palaeolatitude of 75-78° South, the method is based on average growth ring widths and information about the solar radiation regime for 75° South, extrapolated from modern data at similar northern latitudes.

The following section discusses influences on solar radiation receipt, the applicability of modern conditions to the geological past and an estimate of the total radiation receipt for 75° South. The availability of the tree crowns for intercepting direct sunlight at the low solar angles of the high latitudes is estimated by modelling the form of the tree crown and reconstructing the shade regime within the mapped area of forest floor (fossilised stump horizon SOA2, Section 4.44). The maximum possible net wood productivity for both shaded and unshaded trees in the predicted radiation regime is then calculated. To compare these results with information from the fossil record, the net wood productivity is calculated from samples collected from two fossil tree stumps at Kawhia Harbour, representing trees originally from the canopy (shaded) and emergent (unshaded) forest layers. Net wood productivity can be used to estimate the total forest productivity (Creber and Francis, 1987) which is compared with the modern day geographical distribution of vegetation types of similar production.
To realistically model the solar radiation regime for a specific latitude and extrapolate the information into the geological past, certain assumptions must be made and the influences on modern day solar radiation considered. The primary assumptions are that the radiative intensity of the Sun, the distance and the orientation of the Earth from the Sun, the Earth’s orbit, orientation of the Earth’s axis and the amount of solar radiation reaching the Earth’s surface have all remained approximately constant (Specht, et. al, 1992) since at least Middle Jurassic times. A further assumption is that the solar radiation regime in the Northern Hemisphere parallels that of the Southern Hemisphere. These assumptions are based on common sense and a basic knowledge of the Earth and Sun’s astronomical configuration and behaviour. This allows empirical measurements of total surface radiation receipt at 75° North per day during June and at the end of August at Resolute on Cornwallis Island, Arctic Canada (Warren Wilson, 1966) to be extrapolated to 75° South - the palaeolatitude of the Temaikan fossil forests under investigation.

Calculation of annual net wood productivity for the Kawhia Harbour forest requires a realistic estimate of the total annual radiation receipt (megajoules per metre squared per year; MJ/m²/y) at 75° South. Solar radiation reaching the Earth’s surface is influenced by many factors including, latitude, season¹, daylength², weather, surface albedo,

¹ Related to latitude.
² Also related to latitude.
elevation and aspect (Barry and Chorley, 1982). Use of empirical measurements from Resolute (Warren Wilson, 1966) take into account the variation of radiation receipt with latitude and season. The diurnal variation in radiation intensity is relatively small at this locality so the effect of daylength is negligible (Warren Wilson, 1966). A further latitudinal effect is a high ratio of diffuse light to direct light in polar latitudes (Warren Wilson, 1966) which would aid the interception of radiation by tree crowns at low solar angles, but cannot be directly accounted for in this calculation.

Polar latitudes tend to have cloudy weather with a radiation receipt 10-15% lower than the mean value for all latitudes in the summer months (Warren Wilson, 1966). Cloud cover and type affects the amount of radiation reflected and absorbed before the radiation reaches the surface. For example, clouds reflect approximately 25% and absorb 3% of incoming radiation in contrast to cloud-free air\(^1\) which reflects 4% and absorbs 21% (Sellars, 1965). If the assumption is made that the year the empirical measurements were made was an average year in terms of cloud cover, then atmospheric influences on radiation receipt are already taken into account by measurement at the surface. This consideration cannot be effectively accounted for in the Temaikana as atmospheric influences were probably significantly different.

The reflectivity of the Earth's surface cover also affects the radiation receipt at any particular location. The land surface during deposition of the uppermost Urawitiki

\(^1\) Including dust particles and water vapour.
Measures strata at Kawhia Harbour is interpreted as being densely covered by dominantly conifer-related trees. Modern coniferous forests have been found to reflect 9-15% (depending on the foliage density) of incoming solar radiation straight back into the atmosphere (Barry and Chorley, 1982). Therefore, the albedo of modern day forests is assumed to be similar to that of the Temaikan fossil forest.

Topographic influences include the affect of site elevation. Generally, the higher the altitude, the less insolation. For example, in the middle latitudes the incident solar radiation intensity increases by 5-15% for each 1000 m increase in elevation in the lower troposphere (Barry and Chorley, 1982). However, other influencing factors then contribute including, increased cloud cover in the mountains and lower air density at altitude affecting the amount of radiation absorbed. The Kawhia Harbour forests are interpreted to have been growing at a relatively low elevation on a near-coastal braidplain, so in a similar setting to Resolute. Further, the fossilised tree stumps preserved in-growth-position within the Urawitiki Measures imply that the local topography was relatively level (p. 135) suggesting that relief shading was minimal\(^1\) and the vegetation received mainly direct insolation.

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\(^1\) However, this only applies to a relatively small area where the trees were growing, so hills could well have been present in the region and inland at the source area.
Estimate of the Total Radiation Receipt at 75° North

At the high latitude of 75° North, the usual light/dark diurnal cycle of the lower latitudes is interrupted by periods of 24 hours daylight and 24 hours darkness. The total number of daylight hours per year (converted to 24 hour daylight days) is required to estimate the amount of time during the year that direct solar radiation would reach the Earth’s surface at this latitude. The number of hours of direct solar radiation at 75° latitude is equal to 186.75 days, derived from the Smithsonian Meteorological Tables (Table 170) for solar altitude and azimuth for 70° and 80° North (List, 1951).

Warren Wilson (1966) measured a total surface radiation receipt at Resolute during the month of June (the month of the Summer Solstice and maximum solar insolation during the year) at 27.8 MJ/m²/day. By the end of August the radiation receipt had decreased to 13.0 MJ/m²/day, suggesting an approximately linear decrease in insolation towards the beginning of the polar night. The sun is below the horizon for 24 hours a day between October 21st and February 23rd, during which the surface only receives the constant background radiation of 0.4 MJ/m²/day. A projected graphical representation of the solar radiation regime throughout the year at Resolute (Figure 5.61) allows the calculation of the total surface radiation receipt at 75° North (including background radiation during the polar night) to be 3082.1 MJ/m²/y. This figure is assumed to be a reasonable estimate of the total surface radiation receipt incident at 75° South during the Temaikan.
Figure 5.61  A graphical representation of the solar radiation regime throughout the year at Resolute, Cornwallis Island in Arctic Canada (75° North). Empirical data after Warren Wilson, 1966.

5.63 Tree Form and Shading

Shading and crown form both affect the ability of the foliage to intercept available radiation and are an influencing factor on net wood productivity. At low solar elevations, Jahnke and Lawrence (1965) estimated that a tree crown with a form close to a geometric cone of height eight times greater than the radius, is the most efficient at intercepting direct solar radiation (Figure 5.62). Dickinson (1983) states that spruce fir forests have very low albedos at low solar angles. The solar beams penetrate well into the crown and much of the back-scattered light is directed downwards to be absorbed by neighbouring trees on otherwise shaded sides. Conifer trees with conical crowns
predominate in the Northern Hemisphere taiga forests, but their distribution is mainly
due to temperature rather than light (Woodward, 1987). Pole (1999) argues that the
conical crown form could well be just part of the conifer’s basic architecture and not
related to solar elevation at all, due to the predominance of flat-topped canopies in the
most southerly (55° South) Nothofagus-dominated forests of South America. There is
no direct evidence of crown form within the Kawhia Harbour fossil forests and either
conical or flat-topped crowns would have a similar total shading effect on the canopy
trees, so the former, being more representative of modern day conifer tree habit, is
assumed.

Topographic shading is interpreted as being minimal or non-existent over the Kawhia
Harbour forest, but neighbouring tall trees in such a dense forest (Section 4.44) could
have significantly restricted the availability of solar radiation to smaller canopy trees. To
investigate the affect of shading within the Kawhia Harbour forest, the tree forms were
reconstructed using empirical measurements made by the author on mature gymnosperm
trees growing within the Wellington Botanical Gardens (Araucaria, Pinus and Sequoia).
The landscaped gardens represent an unnatural growth environment but, with the
measurement of 32 trees, the effect of crown radius influencing factors (for example, soil
type and neighbour proximity) are assumed to be averaged. The results indicated that,
irrespective of species or growth site, the radius of the foliage crown approximated the
height from the stump base to the first foliage branches. However, within a closely
spaced tree stand, the bases of the foliage crowns would be at a similar height at the level
of maximum light penetration towards the forest floor.
Figure 5.62 Graph to show the effective surface area of foliage cones of varying dimensions at different latitudes. A cone with a height eight times its radius is the most effective for solar radiation interception at low solar angles in the high latitudes. After Jahnke and Lawrence, 1965.

Further, again irrespective of species or growth site, that the radius of the foliage crown is approximately equal to twice the trunk circumference. These measurements, interpolated to the fossil trees, allow the reconstruction of each tree from the measured fossil stump diameter. The estimated radius of the foliage crowns (Figure 5.63) correlates with the interpretation of a closed canopy (Section 4.44) for the Kawhia Harbour forest. Tree heights have already been estimated using Mosbruger, et al.'s (1994) equation (Section 4.44).
Figure 5.63  Estimated extent of the foliage crowns of trees (green circles, plan view) within the mapped area of fossil forest floor horizon SOA2 in the Urawitiki Measures, Kawhia Harbour. It is assumed that all trees were alive at the time of inundation. Black dots indicate the location of the fossilised tree stumps. The red dot and circle represent tree 113 used for net wood productivity calculations. The dots are proportional to the fossilised stumps measured diameter.

It is assumed that the leaf density of the crowns is sufficiently high for complete shading and that the leaves in the shade only receive diffuse radiation. It is also assumed that all of the trees were alive when inundated, as dead trees with no foliage only provide negligible shade. Figure 5.64 represents the shade regime within the Kawhia Harbour forest using a height transect through the mapped area of fossil forest floor in horizon SOA2. The transect is taken from south to north, looking west, and represents the maximum elevation of the sun above the horizon during the year at 75° South at noon on
the Summer Solstice\textsuperscript{1}. The geographic orientation of the transect is assumed to represent close to the original orientation due to the palaeogeographic interpretation for the region (Figure 3.2), allowing the positioning of the Sun 38.5° above the horizon to the north of the mapped area. Only the trees represented by fossilised tree stumps within the mapped area are included in the transect, so additional trees could well have surrounded those figured in a similar density and shaded the trees on the northerly edge. In addition, the model is only a two-dimensional transect and does not represent the shading influences of three-dimensional tree crowns.

The projected shadows indicate the minimum amount of shading at this orientation during the year and show the canopy trees in the interior to be completely shaded. The emergent trees protruding through the canopy layer receive direct radiation over at least half of their foliage crown (the north-facing side). Tree 113 is used for an estimate of net wood productivity.

\textsuperscript{1} The day is assumed to be cloudless.
5.64 Net Wood Productivity Estimates

An estimate of the *maximum possible* net wood productivity for the Kawhia Harbour trees can now be calculated using the derived annual total surface radiation receipt for

Figure 5.64 A transect trending south (left of diagram) to north (right of diagram) through the mapped area of fossil forest floor in horizon SOA2 of the Urawitiki Measures, Kawhia Harbour. Estimated tree crown form and height recreates the shade conditions at the time of growth, if the geographic orientation of the deposit is assumed to have been similar during the Temaikan (see text for further discussion). The diagram represents noon on the Summer Solstice (December 21st) when the sun reaches its maximum altitude for the year at 75° South. Tree 113 is used for net wood productivity calculations and may have been completely shaded from direct solar insolation for the entire year by taller trees.
the locality, assuming a high New Zealand palaeolatitude and that light was the only limiting factor to growth in the Temaikan forest environment\(^1\).

Each tree within the mapped area of fossil forest horizon SOA2 covers 4.25 m\(^2\) of forest floor\(^2\) and with an annual total surface radiation receipt of 3082.13 MJ/m\(^2\)/y, potentially receives 13 099.05 MJ/y. However, 9-15\% is reflected back immediately due to the albedo of the conifer forest (p. 359; Barry and Chorley, 1982), dependant on the foliage density, so 11 920.13 - 11 134.19 MJ/y is intercepted by the tree crown. Only 0.4\% of incoming energy is used to form wood (Kozlowski, 1962), so 44.54-47.68 MJ/y divided by the calorific value of conifer wood (14 KJ/g (gram), Creber, pers. commun., 1996) represents 3.18-3.41 kg of annual wood production. Therefore, the maximum possible net wood productivity of trees receiving direct solar radiation within the mapped area of the Kawhia Harbour forest, at a palaeolatitude of 75\(^\circ\) South, is 7.48-8.02 t/ha/y.

Only 25\% of incoming radiation reaches a shaded tree (Montieth, 1973), so the total annual radiation receipt of a canopy tree within the mapped area of the Kawhia Harbour forest would equal 2783.55-2980.03 MJ/y. Taking into account the amount of incoming energy used in wood production and the calorific value of conifer wood, the net wood productivity of a shaded canopy tree would equal 0.80-0.85 kg/y. Therefore, the maximum possible net wood productivity of trees receiving only diffuse solar radiation within the mapped area of the Kawhia Harbour forest, at a palaeolatitude of 75\(^\circ\) South, is

\(^1\) Soil moisture and nutrient availability are assumed to be at optimum levels.
\(^2\) Twenty-four fossil tree-sized stumps are distributed over the mapped area of 102 m\(^2\).
1.88-2.00 t/ha/y. The upper estimated figure for net wood productivity could well be the most representative figure for the Kawhia Harbour forest due to the high density of the trees, implying a high foliage density and a higher albedo.

All calculated figures of net wood productivity from the growth ring analyses of fossilised tree stumps preserved in-growth-position at Kawhia Harbour must be less than the derived maximum figures. Growth ring sequences were measured from three stump samples within the mapped area (stumps 84, 113 and 114, Figure 4.412), all representing trees of canopy level height.

The net wood productivity of stump 113 is calculated as an example, due to its interior position within the mapped area and it has the longest, so most representative, measured growth ring sequence of the three. The volume of wood within the tree trunk is visualised as a circular-based cone of radius 0.115 m (the measured fossilised stump radius) and height 9.05 m (derived from Mosbrugger, et al.'s (1994) equation). The volume of the cone (prior to a season's growth; \( V_1 \)) is equal to 0.1253 m³ and is calculated using the following formula (Creber, pers. commun., 1996):

\[
V = \frac{\pi r^2 h}{3}
\]

where \( r \) is the basal radius (m) and \( h \) = the estimated tree height (m). Following a season's growth, the volume of an additional growth ring has been added to \( V_1 \). To
approximate an average season’s wood production, the average growth ring width from the measured sequence (0.88 mm) is added to the cone’s radius and the volume recalculated \( V_2 = 0.1273 \text{ m}^3 \). The volume added by the new season’s ring is represented by \( V_2 - V_1 \), which equals 0.0020 \text{ m}^3. A typical density for modern conifer wood is 414 kg/m\(^3\) (Creber, pers. commun., 1996), so the mass of the new growth ring is 0.83 kg. This represents an annual net wood productivity of 1.95 t/ha close to the maximum possible for a shaded tree within the Kawhia Harbour forest.

An estimate of annual net wood productivity for an unshaded tree of emergent height was not possible within the mapped area of horizon SOA2 due to poor preservation of suitably large stumps, so assuming the tree density is the same throughout the forest horizons, a sample from stump 25 in horizon OPB2 is investigated. Following the same method, the estimated annual net wood productivity for this tree is 3.39 kg (7.98 t/ha), which again is close to the maximum possible for a unshaded tree within the Kawhia Harbour forest. Table 5.5 summarises the net wood productivity results for the trees investigated compared to the maximum possible figures calculated. The high net wood productivity values calculated for both canopy and emergent trees suggests that the overall photosynthetic efficiency was very high and the trees were maximising wood production from the available solar radiation.

The method of calculating annual net wood productivity from fossilised wood is limited by several factors. For example, it is unknown how representative the observed growth ring widths are of the original dimensions. In addition, within modern trees, the density
of wood varies within a tree, along and across the stem axis, between trees and individual stands and also perhaps with increased elevation above sea level and latitude (Assmann, 1970), so the figure used may not be entirely representative of the original tree.

Table 5.5   Summary table of net wood productivity estimates and actual data for shaded and unshaded trees in the Kawhia Harbour fossil forest.

<table>
<thead>
<tr>
<th></th>
<th>Net Wood Productivity (t/ha/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum possible at 75° South</td>
</tr>
<tr>
<td>Shaded (canopy) tree</td>
<td>1.88-2.00</td>
</tr>
<tr>
<td>Unshaded (emergent) tree</td>
<td>7.48-8.02</td>
</tr>
</tbody>
</table>

However, the calculations are considered reasonable estimates from the available information.

Annual net wood productivity was calculated for all the samples with growth ring sequences in the fossilised tree stump horizons assuming the same forest density as horizon SOA2 and the results are summarised in Table I7, Appendix I. All of the estimates, except those derived from stumps 8, 44 and 211, are within the maximum possible limit of annual net wood productivity for either canopy or emergent trees. The range of annual net wood productivity within the canopy of all horizons is 0.24-2.35 t/ha/y and for the emergents is 2.52-10.45 t/ha/y. The annual net wood productivity figure calculated for stump 8 (2.33 t/ha/y) could well be over-estimated due to the mean growth ring width representing only a very short sequence of seven consecutive rings.
from the inner part of the stem. Although stumps 44 and 211 have longer consecutive ring sequences (22 and 17 rings, respectively), the samples were also collected from the inner stem radius, indicating that productivity could also have been over-estimated with 2.35 t/ha/y and 10.45 t/ha/y respectively. There is no similarity of annual net productivity results within each taxa, or from samples collected from different parts of the stem radius, but canopy tree estimates are consistently ≤1.00 kg/y and emergent tree estimates are >1.00 kg/y. There is not enough well-preserved material to investigate annual net productivity differences between horizons.

5.65 Whole Forest Productivity and Biomass Estimates

Annual net wood productivity (t/ha/y) estimates in modern forests have been shown to be equivalent to ~40-50% of the total forest productivity in the area under investigation (Creber and Francis, 1987). Applying the proportion of canopy to emergent trees within the mapped area and their respective annual net wood productivities, an estimate of the total productivity of the Kawhia Harbour forest can be made. Within the mapped area of horizon SOA2, there are 17 trees of canopy height (≤10.0 m) and 7 trees of emergent height (>10.0 m). Therefore, the total annual productivity for the canopy trees within the mapped area can be estimated at 14.11 kg/y and for the emergent trees at 23.73 kg/y. The total annual net wood productivity for the trees within the mapped area is 37.84 kg, which is equivalent to 3.71 t/ha. Therefore, total forest productivity can be estimated at 7.42-9.28 t/ha.
Plotting the total annual radiation receipt at 75° South on to Hall’s (1979) graph of expected annual plant yields as a function of solar radiation (Figure 5.65), we would expect a higher total forest productivity of ~10 t/ha/y at a photosynthetic efficiency of 0.5%¹. Factors within the Kawhia Harbour forest environment that could have reduced the forest productivity from the expected level include the low angle of incident sunlight and closed canopy restricting the undergrowth development. Further, we have assumed that light is the only limiting factor to growth, but, nutrients or water may have been in short supply and so restricted growth rates². In addition, the total forest productivity estimate is calculated from the annual net wood productivity estimate from only two trees, so a larger data set may provide a figure closer to the expected.

Another productivity parameter commonly estimated for modern forest ecosystems is biomass, or the total weight of all the organic matter within a specified area at any given time. For an exact calculation of forest biomass, the total weight of all the tree trunks and crowns is required, but this can be estimated from the radius of the tree trunks near their base. Murray (1927) devised a formula that relates trunk circumference to the fresh weight of the tree, independent of species:

\[ w_f = 7.08c^{2.49} \]

¹ Taking the most conservative estimate of photosynthetic efficiency as we are investigating plant growth in high latitudes.
² It is assumed that water would not have been in short supply for sufficiently long periods to affect growth due to sedimentological and palaeobotanical evidence already discussed.
where \( w_t \) = fresh weight (g) and \( c \) = trunk circumference (cm). If dry weight is assumed to be equivalent to 45% of the fresh weight (Mosbrugger, et al., 1994), then the approximate biomass for the Kawhia Harbour forest within the mapped area at Kawhia Harbour can be estimated from the measured fossilised stump diameters. The total fresh weight of all 24 trees within the mapped area calculates at 13.112 t, which is equivalent to 1285.49 t/ha if extrapolated for the whole forest. Therefore, the total dry weight, or forest biomass is estimated at 578.47 t/ha. Pole (1999) estimates the biomass of the Curio Bay fossil forest to be 579-617 t/ha (for stems >8.0 cm and >10.0 cm diameter respectively) which is approximately the same as that for the Urawitiki Measures forest at Kawhia Harbour. These figures do not appear to reflect the differences in structure.
observed with the Kawhia Harbour forest containing a high density of trees >8.0 cm diameter and a higher basal area than Curio Bay.

**Comparison to other Fossil Forest and Modern Forest Ecosystems**

The net wood productivity of the Kawhia Harbour trees, between 1.95 and 7.98 t/ha/y, can be compared to 4.6 t/ha/y estimated for the Alexander Island, Antarctic Peninsula (Lower Cretaceous) fossil forest (Creber and Chaloner, 1984b) and 12.0 t/ha/y estimated for the mid Eocene-early Oligocene Axel Heiberg fossil forest in Arctic Canada (Francis, 1991). The net wood productivity of the canopy level trees (1.95 t/ha/y) within the Kawhia Harbour forests is low compared to the other fossil forests, but the tree density is much greater suggesting that the low productivity could well be due to poor light availability in and below the canopy. In the Alexander Island and Axel Heiberg forests, the trees were more widely spaced (for example, Figure 1.24) allowing more light to reach the foliage crowns and penetrate to the forest floor. However, the net wood productivity estimate for the emergent trees in the Kawhia Harbour forest (7.98 t/ha/y) lies between the figures for the Alexander Island and Axel Heiberg forests, correlating with a much higher interception of light by the foliage crown.

The productivity and biomass estimates for the Kawhia Harbour forest are difficult to compare with modern forest calculations due to the variation in the methods of measurement and the varying stand ages\(^1\). However, total estimated forest productivity

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\(^1\) Younger trees have a higher productivity than older trees (Brinson, in Lugo, et al., 1990).
for the Kawhia Harbour forest (7.42-9.28 t/ha/y) is within the range of that for modern freshwater riverine forests between 1.77 and 17.88 t/ha/y (Brinson, in Lugo, et al., 1990) and also compares well to productivity figures for Northern Hemisphere boreal forests at 8.0 t/ha/y (Wiegolaski, 1978).

The biomass estimates for the Kawhia Harbour forest (578.47 t/ha) and the Curio Bay forest (579-617 t/ha) are high compared to most modern riverine forests at 100-300 t/ha (Brinson, in Lugo, et al., 1990) and the mean estimate for mature temperate ecosystems at 300-500 t/ha (Woodwell and Whittaker, 1968). The higher biomass estimate for the Kawhia Harbour forest reflects the extremely high tree density, even without a significant undergrowth, but the estimate for Curio Bay (579-617 t/ha, Pole (1999)) is anomalous with a lower tree density (Section 4.44).

Productivity is mainly affected by the temperature and light regime at the site of growth, but temperature was not limiting for the Kawhia Harbour trees. The relatively low net wood productivity and total forest productivity suggests that the growth rate of individual trees within the Kawhia Harbour forest may have been restricted by the light regime (specifically the low solar elevation and variable daylengths throughout the year) if a high New Zealand palaeolatitude is assumed. However, the high biomass implies prolific tree growth which suggests that the plants could well have been highly adapted.

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1 This interpretation is based on sedimentological evidence, the presence of traditionally warm climate cycad and araucarian trees and evidence from the O₂ isotope records from belemnites that suggests New Zealand had a warm-temperate climate in the Jurassic (Stevens, 1971).
and ecologically very successful in the high palaeolatitudes. Vaartaja (1962) referred to such highly adapted trees as *photoperiodic ecotypes*.

Global productivity (or the aggregate annual increment, totalling the above-ground and below-ground parts) of plant communities has been modelled by Bazilevich, et al. (1971) (Figure 5.66). Creber and Francis (1987) do not specify whether their estimate of bole wood productivity approximates 40-50% of the aggregate annual increment of a forest or just the above- or below-ground increments, so the estimated total forest productivity figure for the Kawhia Harbour forest must be considered a maximum figure. The Kawhia Harbour total forest productivity range of 7.42-9.28 t/ha/y falls mainly within Bazilevich, et al.'s (1971) productivity Class VI (8.1-10.0 t/ha/y), which is arbitrarily defined as a *middle* range or *medium* productivity. Global distribution of Class VI includes the tropical woodlands (Bazilevich, et al., 1971) which is also equivalent to that estimated for the Alexander Island fossil forests (10 t/ha/y total forest productivity; Creber and Francis, 1987).

Bazilevich, et al. (1971) also studied the relationship of plant productivity to the hydrothermal regime stating that the amount of productivity depends on the balance between the incoming radiation and the energy required for the total evaporation of the annual rainfall. Therefore, productivity is influenced by the *radiation index of aridity*, which is denoted by R/Lr (R = local annual radiation receipt; L = latent heat of vaporisation of water and r = local annual rainfall). Productivity is maximum when R/Lr approaches 1.0 (moist) and decreases thereafter (inadequate moisture). Creber and
Figure 5.66 Global distribution of the total productivity (aggregate annual increment, t/ha of dry matter) of plant communities. Productivity Class VI is equivalent to that calculated for the Urawitiki Measures fossil forests at Kawhia Harbour. Numbers refer to vegetation types as quoted in Bazilevich, et al., 1971. Class VI mirrors the distribution of the tropical woodlands (number 25, outlined in red). After Bazilevich, et al., 1971.

Francis (1987) estimated that the environmental conditions at the Alexander Island fossil forests could well have represented an aridity index approximately equal to one, indicating the ecosystem was at an optimal productivity level for the environment. An aridity index of approximately one is also estimated for the Kawhia Harbour forests based on Bazilevich, et al.,’s (1971) graph of annual increment versus aridity index.
(Figure 5.67). The graph also implies that the Urawitiki Measures vegetation could well have been growing in a warm thermal zone.

![Graph](image)

**Figure 5.67** Graph indicating the dependence of the annual productivity of plant communities on the humidity conditions in different thermal zones. 1, temperate warm zone; 2, warm zone; 3, very warm zone. After Bazilevich, et al., 1971.

### 5.66 Summary

Net wood productivity estimates for the Temaikan trees at Kawhia Harbour, assumed to have been growing at high palaeolatitudes, using fossilised tree stumps preserved in-growth-position and empirical measurements of the light regime at modern high latitudes, have shown that cell production was maximised for the radiation available during the near-polar summer. The form of the tree crown may have been tall and conical to intercept as much of the low angle solar radiation as possible during the
growing season. The annual net wood productivity of the shaded canopy trees was much lower than that of the unshaded emergent trees. However, annual net wood productivity has also been shown to be maximum for the setting and assumed palaeolatitude, for both shaded and unshaded trees. Therefore, high annual net wood productivity figures imply specific adaptation to a high palaeolatitude light regime. Net wood productivity for other high palaeolatitude forests compare well to the Temaikan forest figures if differences in forest density are considered.

The estimate of total forest productivity from the Kawhia Harbour fossil forest is less than expected, but within the range of modern freshwater riverine systems. In contrast, the biomass (from both Kawhia Harbour and Curio Bay fossil forests) is high compared to most modern riverine forests. Total forest productivity is considered to be medium compared to world-wide forests and is approximately equivalent to tropical woodlands growing in warm thermal zones. Bazilevich, et al.’s (1971) radiation index of aridity suggests that the ecosystem was at an optimum productivity level for the environment.

5.7 SUMMARY

Interpretations made from the results of the growth ring analyses reflect the physiology of the original plants, the nature of the forest environment, climatic conditions and characteristics of the growing season. Fossil wood from the New Zealand Temaikan shows similar growth patterns to late-early Permian Antarctic fossil wood. The data set
of growth ring characteristics from Slope Point fossil wood, near Curio Bay, is too small for significant comparisons.

Overall, observed differences in growth ring characteristics within the Kawhia Harbour fossil wood were not species dependant and did not reflect varying positions of the sample within the stem radius. This suggests that internal factors were not the main influence on growth rate. However, _Protopodocarpoxyylon_ sp. samples exhibited wider tracheid cells and dominantly complacent growth compared to the other taxa, suggesting that internal factors were affecting cell production in this taxa.

Interpretation of the growth rings analysed provided much information about the climate and growing season at the time of growth of the Kawhia Harbour and Allan Hills forests. The lack of frost rings in the sequences implies that temperature was not limiting to growth at any time throughout the growing season. The sharp growth ring boundaries and analysis of individual rings suggest the growing season was a clearly defined period of the year similar to the Polar Day present at high latitudes today. The beginning of the growing season saw a rapid rise to temperatures favourable for growth (growth begins at about 6°C for many plant species; Jones, 1979) probably related to an increase in photoperiod at the beginning of the Polar Day. During the first half of the growing season, usually short-lived disruptions to cell production occurred, which could have been due to fluctuations in water supply (too little or too much) or the occurrence of severe storms. The end of the growing season may have been rapid as temperature and
photoperiod decreased below a critical level and cambial activity ceased for the duration of the Polar Night.

In the Kawhia Harbour samples, variation in the number of cells per ring and the ring widths implies that environmental conditions could vary significantly from year to year. Periodicities, defined by eye, within the longest ring width sequences from the outer stem radius imply cycles of 4-6 years and ~20 years in duration between particularly unfavourable growing seasons. These cycles may have been related to solar or volcanic activity along the Gondwanaland arc margin. Periodic patterns observed in two of the Allan Hills growth ring sequences indicate further collecting and statistical periodicity analysis is required to adequately identify growth cycles.

The growth ring width sequences from the Tamaikan Kawhia Harbour and late-early Permian Allan Hills trees exhibited both normal and abnormal growth patterns. Abnormal growth, with rings generally widening as the tree ages, could well have occurred due to poor light availability beneath the closed canopy during early growth. As height was slowly gained through the canopy, more light became available and the growth rate increased. This forest situation may have occurred in the Kawhia Harbour forest, but the vertical structure of the Allan Hills fossil forest is unknown due to a lack of preserved in-growth-position stumps.

The observed variation in ring width year to year, from Kawhia Harbour and Allan Hills samples, could well have been significantly influenced by the site of tree growth. For
example, trees at the forest margin or on the edge of clearings would have been more sensitive to changes in environmental conditions (reflected in more variable growth ring width sequences) than in the relatively stable environment of the forest interior. However, the majority of samples from both the Kawhia Harbour and Allan Hills collections have high mean and maximum ring widths implying that rapid growth was possible during growing seasons when the conditions were favourable, regardless of growth site. The growth ring width data for both the Kawhia and Allan Hills forests compares well to that of other high palaeolatitude fossil floras, from both hemispheres, but the wider rings imply growing conditions were more favourable in the geological past than those near the modern tree-lines. The growth rate of the Kawhia Harbour trees compares well to that of modern Cupressaceae trees in Queensland, Australia, in an approximately tropical climatic regime at 17° South.

Broad interpretations on the vertical and lateral structure of the forests can also be made from the growth ring analysis. The total lack of reaction wood implies that the local topography at the site of tree growth was relatively level with minimal or non-existent relief shading. Further, a lack of reaction wood in the Kawhia Harbour trees correlates with the interpretation of a closed canopy, implying vertical stem growth unaffected by nearby open areas of the canopy.

The Mean Sensitivity results for the Kawhia Harbour fossil forest suggest that there may have been a forest margin at the site of the Totara Peninsula section. In addition, throughout the rest of the forest, clearings may have occurred, rimmed by trees with
sensitive growth patterns. The reconstruction of a north-south transect through the mapped area of horizon SOA2 suggested that the canopy trees could well have been completely shaded by taller emergents throughout the growing season at low angles of solar elevation. The complete shading of the forest floor could well have restricted undergrowth and been a cause of the lower than expected total forest productivity estimate.

The late-early Permian Allan Hills trees showed predominantly complacent growth patterns implying generally favourable environmental conditions year to year in the Gondwanaland continental interior. The extremes of climate that could well have occurred in the interior of the supercontinent do not appear to have adversely affected tree growth. In contrast, the trees appear to have adapted very well to the prevailing climatic conditions. The sensitive growth patterns of some of the Temaikan trees which were growing on the coastal plain may have reflected general exposure on the continental margin, but a much larger data set is required to adequately test the effects of continentality.

Net wood productivity values from samples in Kawhia Harbour representing trees both within the shaded canopy and unshaded emergents, are close to the maximum possible at 75° South. These values imply that the Temaikan trees, assumed to have been growing at high palaeolatitudes, maximised wood production from the available solar radiation, despite the low angle of solar elevation in the high palaeolatitudes. The very high annual net wood productivity compared to the maximum possible calculated could well indicate
that the plants grew within the optimum temperature range for photosynthesis and productivity of 15-25°C (Creber and Chaloner, 1984b). The net wood productivity of emergent trees compares well with other high palaeolatitude fossil forests, but the canopy tree figure is much lower reflecting the poor light availability at this level. The total forest productivity is estimated to be optimal for the environmental conditions and comparable to modern freshwater riverine and boreal forests. The biomass is high for the Kawhia Harbour fossil forest due to the very high tree density. Global distribution of plant communities of a similar level of total forest productivity mirror that of the tropical woodlands occurring in warm thermal climatic zones.
CHAPTER 6
CONCLUSIONS

The depositional setting of the terrestrial sediments of the Middle Jurassic Temaikan stage in New Zealand can be envisaged as being an approximately north-south trending coastal plain on the margin of the Murihiku basin and east of arc mountains on the south-eastern edge of Gondwanaland (Figure 3.2). The coastal plain, in the vicinity of proto-New Zealand, was extensively vegetated throughout the Temaikan, for a distance at least equivalent to the length of South Island today. The arc mountains were the source of an abundant supply of dominantly sand grain-sized, volcanlastic sediment, reflected in a rapid sedimentation rate at the sites of deposition of the Urawitiki Measures and Curio Bay sediments. The Murihiku basin coastline prograded seawards throughout the early-mid Temaikan from a fan-delta complex to a sandy merged fan-toe braidplain which was vegetated above marine influence. The high sedimentation rate and brief marine incursion at the end of Urawitiki Measures deposition at Kawhia Harbour was the result of a pulse of tectonic subsidence prior to the Rangitata Orogeny.

The Temaikan vegetation was dominated by representatives of the Filicopsida and Gymnospermopsida, but many different taxonomic groups were represented in the fossil record. The vegetation consisted of a multi-layered forest with undergrowth, canopy and emergent levels. The development of the undergrowth was dependant on tree density which was particularly high at the Kawhia Harbour study site and was reflected in the
abnormal growth patterns of young trees. The canopy level was developed between 5 and 10 m at Kawhia Harbour and much lower, between 1 and 5 m, at Curio Bay. The emergent trees were also taller at the Kawhia Harbour forest, reaching 25.6 m. There is evidence for a plant succession dependant on differing levels of soil moisture, of similar taxonomic composition, at both localities. Chlorophyta and Isoetales colonised saturated ground, with a gradation through ferns and cycads to gymnosperm trees on relatively well-drained soils.

The undergrowth composition of the Temaikan vegetation (including components from both Kawhia Harbour and the Curio Bay region) consisted of herbaceous Bryophyta, Lycopodiales, Equisetales and Filicales with shrubby Filicales, Marattiales and Gymnospermopsida. The tree flora was composed of Caytoniales, Coniferales, Cycadales, Cycadeoidales and rare Filicales, but no evidence of Ginkgoales was found. The lack of Ginkgoales is unusual for a Jurassic vegetation, perhaps implying that these plants were not suited to a coastal habitat. The life form of the Caytoniales and Coniferales may have included tall, conical foliage crowns in order to maximise the interception of incident radiation at the low solar angles of the high latitudes.

Several trees from the Kawhia Harbour fossil forest show sensitive growth patterns, probably in response to soil moisture variation (related to growth site as well as the general climatic regime), but overall the trees show high mean and maximum ring widths. Minor variations in the association of plant taxa between the Kawhia Harbour and Curio Bay region study sites could well be due to differences in habitat,
palaeogeographical location and/or the evolution of the coastal vegetation composition between the times of deposition of the sediments at each locality.

Modern trees at high latitudes are limited by low temperature and the polar light regime. However, the Temaikan trees, assumed to have been growing at high palaeolatitudes, were not limited by low temperature (shown by the lack of frost rings) and the annual net wood productivity of these trees is almost equivalent to the maximum possible at 75° South, even in the shaded canopy. This level of productivity implies the Temaikan trees may have been growing in the optimum temperature range for photosynthesis and productivity which for modern plants is 15-25° C (Creber and Chaloner, 1984b). The total fossil forest productivity level of 7.42-9.28 t/ha for the Kawhia Harbour fossil forest compares well with modern tropical woodlands which are globally distributed throughout warm thermal climatic zones.

The similarity in growth patterns between the New Zealand Temaikan and Antarctic late-early Permian trees provides favourable evidence for New Zealand occupying near-polar latitudes during the Temaikan. The forest trees had become highly adapted to a distinct growing season, comparable to that at 80° South today, to the extent of maximising their productivity from the available solar radiation during the polar summer.

The lack of monodominant, dense leaf beds suggests that the Temaikan trees did not have a deciduous adaptation to enable survival throughout the continual darkness of the Polar Night. The maximum possible annual net wood productivity levels suggest they could
well have retained their leaves throughout the polar winter. Photosynthesis would have occurred throughout the period of favourable photoperiod and temperature without a delay during the production of a new season’s leaves. However, leaf mats may simply not have preserved, especially in an active fluvial palaeoenvironment, or may be represented by the homogeneous thin coal layers, so such conclusions can only be subjective.

To achieve the high levels of annual net wood productivity at the assumed high palaeolatitudes, photosynthesis may have occurred continuously throughout the daylight hours of the polar summer. However, the lack of a relatively equable diurnal light pattern throughout the year would require specific adaptations to the physiological processes known to occur in modern lower latitude photosynthetic plants. To prevent the accumulation of waste gases during the period of 24 hour daylight in the middle of the growing season, the trees could have respired simultaneously to the process of photosynthesis. Further, respiration could not have occurred continuously out of the growing season as the assimilated food reserves would have become severely depleted. Therefore, to survive the period of continual darkness, the trees must have undergone complete metabolic shutdown, with minimal transpiration occurring during the winter (due to low evaporation rates) so that leaf desiccation would not be too severe. Such physiological adaptations to the high palaeolatitude light regime would be significantly different to the processes of photosynthetic plant growth in modern vegetation.

Perhaps as a result of their specialist adaptation, the Temaikan trees do not compare well to modern high latitude trees which are commonly growing at the limit of their
ecological range. Clearly, the growth rates and diversity suggest that the Temaikan trees were well within their ecological limits. Therefore, explanations regarding a change in the polar light regime to allow vegetation growth at high palaeolatitudes in the geological past are no longer necessary. For example, high rates of net wood productivity during the near-polar summer in the Temaikan, calculated using modern light regime conditions, at today's astronomical configuration, negate the need for a change to the Earth's axial tilt or an increase in the Solar Constant (Section 1.2). These trees are more comparable to tropical vegetation, but they consistently produce annual rings due to a period of low or zero photoperiod (in addition to low moisture conditions) during the winter months which defines a distinct summer growing season.

Sedimentological and palaeobotanical evidence from the fossil record at the two New Zealand study sites provides significant information about the Temaikan climate on the south-eastern margin of Gondwanaland. High forest productivity, diverse herbaceous plants and warm-temperate sea temperatures (Stevens, 1980a, 1985a) suggest the climate was warm with no seasonal temperature extremes and moderately high rainfall for at least part of the year. Growth ring patterns suggest favourable growing conditions overall with occasional periods of highly variable rainfall within the first half of the growing season. During seasons of exceptionally high rainfall in the source mountains, at least every 100-150 years, run-off floods would inundate and destroy the coastal plain forests. A new, raised palaeosurface would be formed of dominantly sand grain-sized sediment which vegetation would re-colonise over the following years. In general, the south-eastern Gondwanaland coast had warm, wet summers and cool winters moderated
by the warm seas. There is no evidence from the sediments or fossil flora for the amount of rainfall, or the occurrence of snow or frost during the winter season.

The characteristics of the Temaikan climate derived from the fossil record cannot be compared directly to modern climatic regimes due to the age of the deposits, different global continental distribution, oceanographic circulation changes and the derivation of only relative temperature and precipitation information from the fossil record. However, the most appropriate modern day equivalents are the climates of the mesothermal zone.

The mesothermal zone is defined as having one or more months with a mean temperature $<18^\circ C$ with no month with a mean temperature below $-3^\circ C$ and at least one month $>10^\circ C$ (Koeppe and de Long, 1958). The Temaikan climate characteristics compare well with the division of this zone that has hot, moist summers and mild, dry winters. Despite annual net wood and forest productivity levels that compare well to modern tropical vegetation\(^1\), the more comparable mesothermal climates have a distinct summer and winter season, but the summers are generally too warm to be classed as temperate. The modern vegetation that occurs in areas with this climate is variable, but

\(^1\) Possibly due to continuous and rapid cell production throughout the growing season.
forest vegetation once prevailed indigenously over the majority. The forests consist of
broadleaf deciduous, semi-deciduous broadleaf evergreens and broadleaf deciduous trees
in contrast to the presumed evergreen gymnosperms of the Temaikan (Koepe and de

The Temaikan fossil flora record provides an empirical case study of past climate that
can be used as a datum for testing the reliability of computer-driven climate models.
These climate models are known as General Circulation Models (G.C.M.s) and express
in mathematical form what is known of the processes that dictate the behaviour of the
atmosphere and the ocean in the modern day (Barron, 1995\(^1\)). There are an increasing
number of different G.C.M.s used (for example, UKMO (United Kingdom
Meteorological Office\(^2\)), UGAMP (Universities Global Atmospheric Modelling
Programme\(^3\)), GISS (Goddard Institute for Space Studies\(^4\)) and GFDL (Geophysical
Fluid Dynamics Laboratory\(^5\)), but it is beyond the scope of this study to review specific
models (a general review of models used for simulating past climates can be found in
Crowley and North, 1991).

G.C.M.s have been primarily used in recent years for predicting the response of the
climate to increases in greenhouse gases. They include the interaction of the atmosphere

\(^1\) Barron, E.J., 1995. Climate Models: How Reliable are Their Predictions?
   Website: http://gcrio.ciesin.org/CONSEQUENCES/fall95/mod.html
\(^2\) Website: http://www.met-office.gov.uk/sec5/NWP/NWP_computers.html
\(^3\) Website: http://www.met.rdg.ac.uk/ugamp/ugamp.html
\(^4\) Website: http://icp.giss.nasa.gov/abstracts/si96/pinatubo.SBKBSD.html
\(^5\) Website: http://www.ncdc.noaa.gov/ol/climate/online/gcm1000.html
with the oceans and the surface of the Earth, including plants and other ground cover. At present, the resolution of the models is coarse and regional detail is restricted, but the reliability of the models can be tested with modern meteorological and oceanic observations as well as information interpreted from the geological record about past climate change. G.C.M.s have been used to simulate global climate characteristics for various periods of geological time based on palaeogeographic continental reconstructions using modern atmospheric and oceanic parameters (for example, Barron and Washington, 1984 (Cretaceous); Chandler, et al., 1992 (early Jurassic); Crowley, 1994 (a review of Palaeozoic and Mesozoic climate models for Pangaea)).

G.C.M.s for Pangaea, produced since the mid-1980s, generally agree in their simulations of the climatic regime of the south-eastern coastal margin of the Gondwanaland supercontinent during the Jurassic (for example, Parrish, et al., 1982; Chandler, et al., 1992; Sellwood, pers. commun., 1998). One suggestion for the early Jurassic is that mean annual surface temperatures were 5-10°C warmer globally than at present, with the high latitudes achieving five times this change (Chandler, et al., 1992). Further, seasonally averaged temperatures in southern Pangaea during the early Jurassic are modelled as having remained above freezing during the winters along the coast, with instantaneous temperatures along the high palaeolatitude coasts dropping below 0°C periodically (ibid.; Figure 6.1).
The south-east Gondwanaland margin is simulated as having a moderately high rainfall throughout the early Jurassic (Parrish, et al., 1982; Figure 6.2), reaching a maximum in the summer primarily due to the uplift of polar air over coastal mountains (Chandler, et al., 1992; Figure 6.3). In addition, seasonal variability in precipitation is modelled to have been enhanced in the Southern Hemisphere during the early Jurassic by the occurrence of monsoon climatic regions on the southern Tethyan margin (ibid.). The
continental interior is unanimously modelled as being relatively arid throughout the year (for example, Chandler, et al., 1992; Figure 6.3). Sellwood (pers. commun., 1998) modelled that cloud type could well have been $\sim$70-80% higher over the polar regions (the effect of this on temperature depends on cloud type) and suggests that no glacial ice would have formed on the southern continents during the Kimmeridgian (Upper Jurassic). However, Sellwood (pers. commun., 1998) also suggests that shallow seasonal snow could well have persisted through the summer months if there was $\geq$1 km of relief in the continental interior.

![Figure 6.2](image)

**Figure 6.2** Predicted distribution of rainfall patterns during the early Jurassic. Numbers are relative values only. $<50 =$ low rainfall; 50-100 = moderately low rainfall; 100-200 = moderately high rainfall; $>200 =$ high rainfall. Light shading = continental shelf; medium shading = lowlands; dark shading = highlands. After Parrish, et al., 1982.
Figure 6.3  Simulated global distribution of early Jurassic precipitation rates showing moderately high rainfall in coastal regions of south-east Pangaea during the summer months. After Chandler, et al., 1992.

The interpretations made from the fossil flora studied during this investigation provide strong evidence for proto-New Zealand occupying a high latitude position during the Middle Jurassic. The growth patterns of the New Zealand fossil trees compare well to the high palaeolatitude Antarctic late-early Permian fossil wood implying the proposed palaeolatitude of 75-78° South for New Zealand is highly probable. Climatic interpretations suggest the south-eastern Gondwanaland margin in the vicinity of proto-
New Zealand at 80° South had a near tropical climate during the Middle Jurassic, in contrast with the cold, arid modern polar climate at this latitude today. Therefore, an explanation is required for the widening of mesothermal climatic zones at least during the Middle Jurassic compared to the modern situation at least down to ~80° South.

High global temperatures during the Middle Jurassic could be explained by the continental configuration and oceanic circulation interpreted from palaeomagnetic studies (for example, Figure 6.2). Pangaea during the Jurassic is interpreted as being divided by the Tethyan ocean in the east forming the early northern Laurasian and southern Gondwanaland supercontinents. This configuration and modelled westerly winds (at least during the south polar summer) along the northern Gondwanaland margin (during the early Jurassic; Figure 6.4) could well have caused a warm boundary current to flow eastwards from the southern Tethys around the south-eastern margin of Gondwanaland (Chandler, et al., 1992). This interpretation could explain the southward migration of Tethyan faunas around the Gondwanaland coast and the absence of a cool-temperate fauna in the New Zealand region at this time (Stevens, 1980a, 1985a).

Chandler, et al. (1992) suggest that once global warming had been triggered, it could have been maintained thereafter by a combination of increased heat transport in the oceans and the positive feedback elements of a lower global albedo (due to the reduction of the polar ice caps) and an increase in atmospheric water vapour (increased ocean evaporation). Therefore, the effects of global warming during the early Mesozoic could be due to the palaeogeographic configuration of the continents without the need for
Figure 6.4  Simulated global distribution of early Jurassic wind vectors. Westerly winds are modelled along the northern Gondwanaland margin during the Southern Hemisphere summer. After Chandler, et al., 1992.

(a) Surface winds (hatched area indicates the approximate position of the Inter-tropical Convergence Zone).

(b) Upper level winds.
variation in the Earth's astronomical arrangement, solar output or an increase in atmospheric CO₂ (Section 1.2).

To conclude, the climate characteristics modelled by current G.C.M.s for the south-eastern margin of Gondwanaland during the Jurassic correlate well with the climatic regime interpreted from coeval fossil flora in New Zealand. The only inconsistency is the large amount of cloud cover postulated for the polar regions (Sellwood, pers. commun., 1998) which could significantly affect the vegetation productivity level. However, the growth patterns suggest the trees were as well adapted to shade conditions at the high palaeolatitudes as to direct sunlight conditions, so net wood productivity would still be maximised even within a predominantly cloudy near-polar light regime. Therefore, climate parameters from the geological past in New Zealand imply that the computer-driven G.C.M.s, in general, provide realistic simulations of global climate (particularly with respect to the Southern Hemisphere), which has important ramifications for the reliability of future global warming predictions from these models.
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